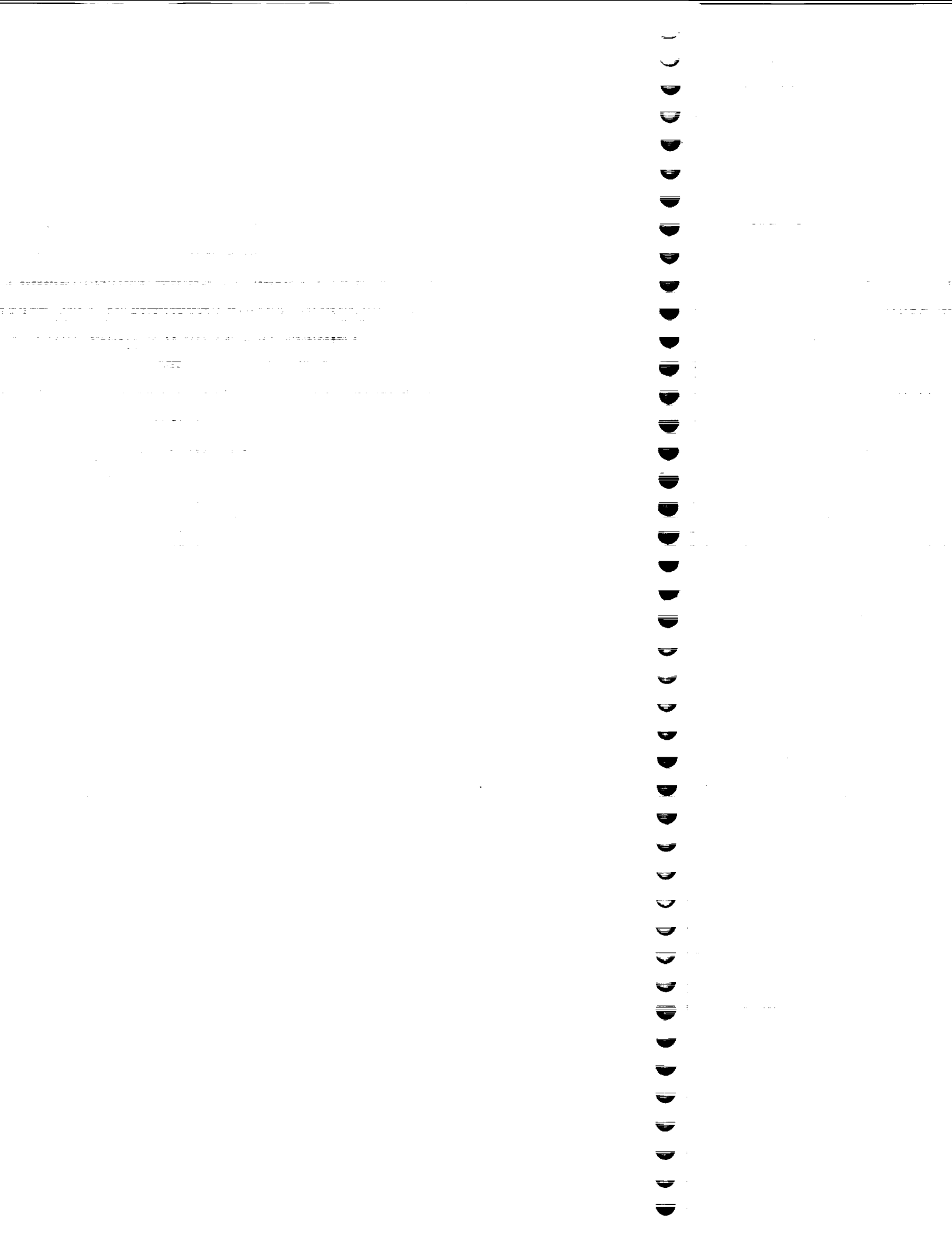
The Center for Space Telemetering and Telecommunications Systems at New Mexico State University - Annual Report 2000-2001

by

S. Horan, P. DeLeon, T. Shay, D. Borah, C. Creusere, and R. Lyman

NMSU-ECE-01-001



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Manuel Lujan Space Tele-Engineering Program
New Mexico State University

Prepared for

NASA Goddard Space Flight Center
Greenbelt, MD

under Grant NAG5-9323

March 21, 2001

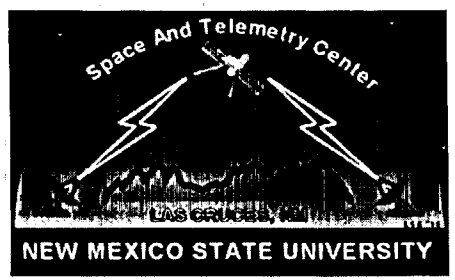
Klipsch School of Electrical and Computer Engineering
New Mexico State University
Box 30001, MSC 3-O
Las Cruces, NM 88003-8001

1) Technical Reports
   a) Horan, Stephen and RuHai Wang, "Enhancement of the NMSU Channel Error Simulator to Provide User-Selectable Link Delays", NMSU-ECE-00-001, March 2000.
   b) Horan, Stephen, "Using Cell Phones from Satellites", NMSU-ECE-00-002, April 2000.
   c) Jiang, Hui and Stephen Horan "Wireless Telemetry and Command (T&C) Program", NMSU-ECE-00-003, April 2000.
   d) Fan, Jin and Stephen Horan, "Implementing Real-Time Radio Propagation Measurements over the Internet", NMSU-ECE-00-004
   e) Anderson, Bobby and Stephen Horan "Three Corner Sat Communications System", NMSU-ECE-00-005, May 2000.
   f) Horan, Stephen and Ru-Hai Wang "Effects of Protocol Options on Data throughput Over a Simulated Space Channel", NMSU-ECE-00-007, June 2000.
   g) Ghrayeb, Ali and William Ryan "Concatenated Coding and Equalization of Data Transmission and Storage", NMSU-ECE-00-008, June 2000.
   h) Anderson, Bobby and Stephen Horan "Three Corner Sat Communications System", NMSU-ECE-00-009, June 2000.
   i) Castro, Julio "A Multidimensional Adaptive Linear Receiver for the Excision of Spatially-Divers Multi-tone Interferences in a Multipath Mobile Environment", Doctorial Dissertation, June 2000.
   j) Horan, Stephen "3 Corner Satellite Communications Link Estimates", NMSU-ECE-00-010, September 2000.
   k) Horan, Stephen "Basic Electronic Design for Proposed NMSU Hitchhiker Payload", NMSU-ECE-00-011, September 2000.
   l) Ryan, William E. "Concatenated Codes for Class IV Partial Response", NMSU-ECE-00-012, September 2000.
2) Presentations
   a) D. A. Hazzard, E. Y. Poliakov "All-Optical Switch in Alkali Vapors,", SPIE OptoSouthwest 2000 ,Conference, Albuquerque, NM, April 10-11, 2000.
   b) D. A. Hazzard, J. Mac Cannell, E. Selves, G. Lee, D. Moore, J. Payne, C. Garrett, N. Dahlstrom "Novel low-data rate full-duplex optical communications link between earth and LEO,", SPIE OptoSouthwest 2000 ,Conference, Albuquerque, NM, April 10-11, 2000
   c) D. A. Hazzard, J. MacCannell, G. Lee, C. D. Garrett, J. A. Payne, N. Dahlstrom, and M. Giles "A Passive Diode Laser Optical Communications Down-link between the Space Shuttle and the Earth,", International Conference on the Applications of Photonics Technology, Quebec City, Quebec, Canada, June 12-16, 2000.
   d) D. A. Hazzard, J. MacCannell, G. Lee, C. D. Garrett, J. A. Payne, N. Dahlstrom, and M. Giles "Lightwire a Full-Duplex Optical Communications Link between Earth and the Space Shuttle,", International Conference on the Applications of Photonics Technology, Quebec City, Quebec, Canada, June 12-16, 2000.
   e) D. A. Hazzard, J. MacCannell, G. Lee, C. D. Garrett, J. A. Payne, and N. Dahlstrom "Lightweight Optical Wavelength Communications without A Laser in

space", , 14th Annual AIAA /Utah State University Conference on Small Satellites, Logan, Utah, August 21-24, 2000

f) Berner, Stephan and Phillip DeLeon " Parallel Digital Architectures for High-Speed Adaptive DSSS Receivers" Asilomar 2000.
g) DeLeon, Phillip and Yunsheng Ma " Normalized, HOS-Based, Blind Speech Separation Algorithms" Asilomar 2000.
h) DeLeon, Phillip "Short-Time Kurtosis of Speech Signals with Application to Channel Speech Separation" 2000 IEEE International Conference on Multimedia and Expo.
i) D. A. Hazzard, J. MacCannell, G. Lee, C. D. Garrett, J. A. Payne, and N. Dahlstrom,"An Earth to Shuttle Optical Communications Down-Link Using a Semiconductor Laser," 3rd Annual Directed Energy Symposium, White Sands, NM and Albuquerque, NM, Oct. 30-Nov. 3, 2000.
j) S. Horan and Ruhai Wang, "Internet-type Protocol Testing in a Small Satellite Environment," IEEE Aerospace Conference, Big Sky Montana, March 2001.
k) S. Horan, "So You Wish to Place Your Satellite on the Internet," Air Force Research Laboratory, Kirtland Air Force Base, February 2001.
l) S. Horan and Ruhai Wang, "Effects of Networking Configuration on Space Channel Throughput," 14th AIAA/USU Conference on Small Satellites, Logan, Utah, August 2000.
m) S. Horan, "The Potential for Using LEO Telecommunications Constellations to Support Nanosatellite Formation Flying," Space Internet Workshop, Goddard Space Flight Center, November 2000.

3) Degrees Awarded
   a) Jin Fan – MSEE
   b) Hui Jiang – MSEE
   c) Bobby Anderson - MSEE
   d) Julio Castro – PhD
   e) Yunsheng Ma – MSEE
   f) Stephan Berner – PhD
4) Patent Applied For
   a) T. Shay, D. Hazzard, S. Horan, and J. Payne, Light Wire Communications System



Communications, Signal Processing and Telemetering Research: Program Review

Lujan Space Tele-Engineering Program

Klipsch School of Electrical and Computer Engineering

Topics

- NMSU Background
- Communications, Signal Processing, and Telemetering Program
- Facilities
- Goddard Hall Remodeling
- Faculty & Staff
- Review Program

NMSU Background

- NMSU is the Land Grant University and NASA Space Grant University for New Mexico
- NMSU is a federally-designated minority-serving university
- NMSU is a Carnegie-I Research University

Communications, Signal Processing, and Telemetering Program

- Leverage and Spin-offs
  - Air Force Nanosatellite Program
  - Air Force Speech Processing Program
  - Navy Data Compression Program
  - Wireless Communications Laboratory
  - Digital Signal Processing Laboratory
  - Star Tracker Development (NMSU & AFRL)

Facilities

- Thomas & Brown Hall
  - Hardware development Laboratory
  - Software simulation Laboratory
  - Digital Signal Processing Laboratory
- Jett Hall
  - Optical Communications Laboratory

Goddard Hall Remodeling

- Goddard Hall to be remodeled
  - NSF, State of New Mexico, private donations to fund renovation
  - Annex Space (~13,000 ft^2) to be used exclusively for research: electro-optics, communications, digital signal processing, and telemetry
  - Completion target: April 2001 (occupy in May)

Goddard Hall Remodeling

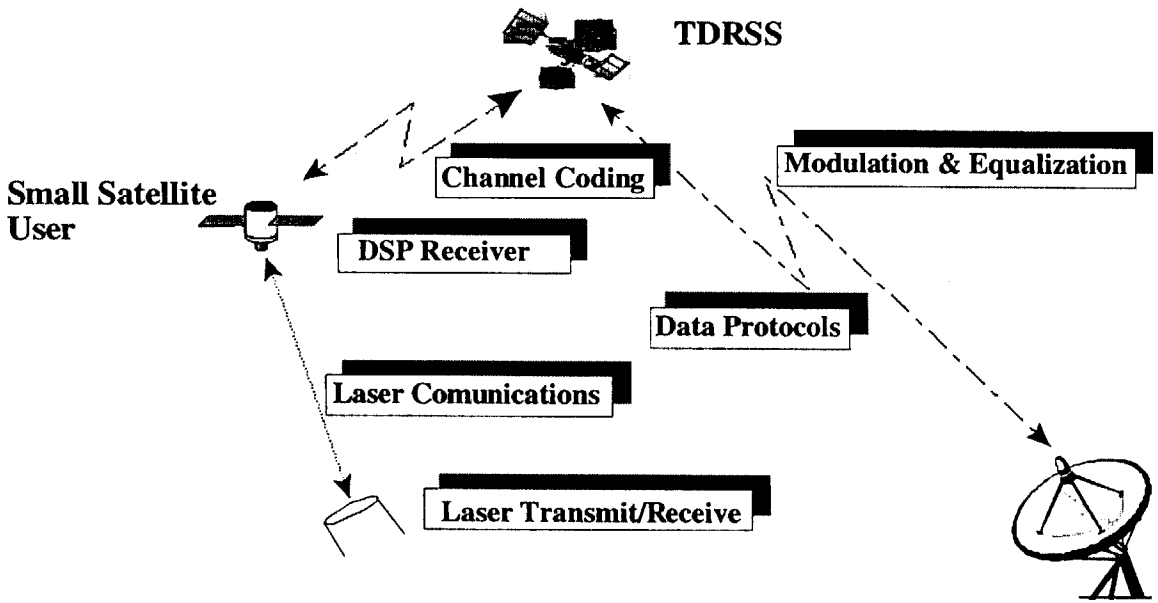
Faculty & Staff

- NMSU Faculty
  - Dr. Stephen Horan - Director
  - Dr. Phillip DeLeon - Associate Director
  - Dr. Deva Borah
  - Dr. Charles Creusere
  - Dr. Raphael Lyman
- NMSU Staff
  - Mr. Lawrence Alvarez
  - Ms. Patricia Anderson

Faculty & Staff

- University of Arizona
  - Dr. William Ryan
- University of New Mexico
  - Dr. Thomas Shay

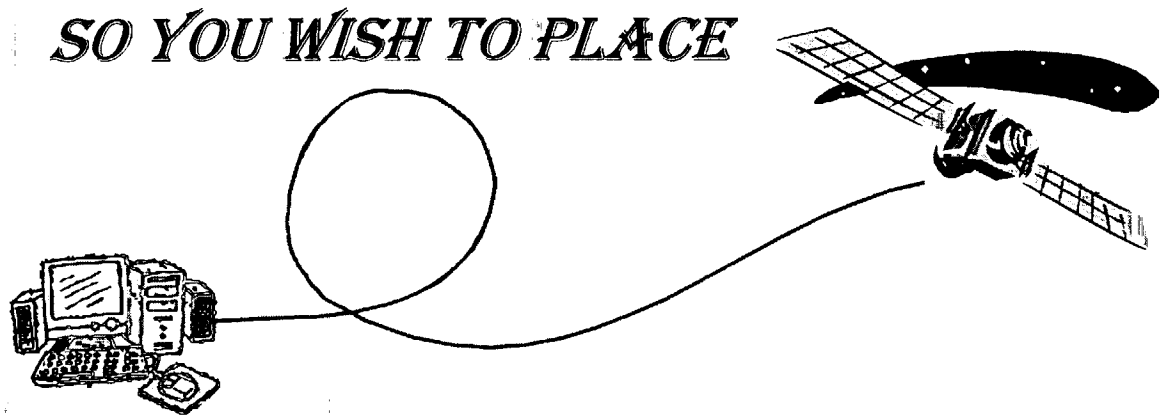
Review Program



Improve access by
- **new techniques for antenna configuration**
- **improved access requests**
- **improved transmission throughput by using more efficient modulation and equalization techniques**
- **improved performance by using improved channel coding techniques**
- **improved data throughput by using data packaging protocols**
- **efficient telemetry transmission through low-power laser communications**

Review Program

- 8:30 - 8:45 Welcome & Introductions
- 8:45 - 9:00 Overview
- 9:00 – 9:45 – Error Correcting Coding
- 9:45 – 10:15 – Video Compression Techniques
- 10:15 - 10:30 Break
- 10:30 - 11:15 – Parallel DSP Techniques for SS Receivers
- 11:15 – 12:00 – FQPSK Modulation
- 12:00 - 1:30 Lunch
- 1:30 – 2:15 – Space Protocol Testing
- 2:15 – 2:45 – Channel Equalization
- 2:45 – 3:00 – Break
- 3:00 – 3:45 – LOWCAL
- 4:00 – 4:30 – Tours
- 4:30 - 5:00 Wrap-up Review
- 5:00 -- Adjourn

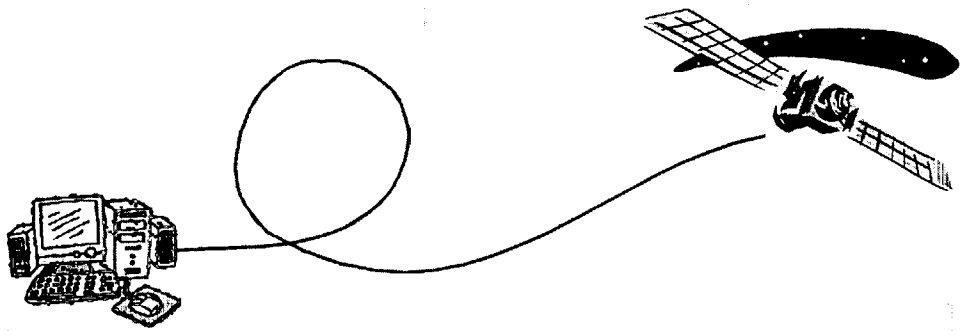


Stephen Horan
Telemetering and Telecommunications Program
Klipsch School of Electrical and Computer Engineering
New Mexico State University

Topics

- Networking Questions
- Development Efforts
- Options Investigations
- Current Experiments
- LEO Telecom Access
- Next Steps
- Future Possibilities

Networking Questions



- Satellite developers wish to operate satellites using the same software, protocols, and techniques as are used in ground testing and in-laboratory development

Networking Questions

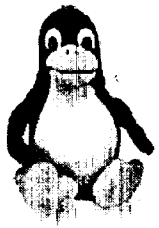
- Pros
  - aids in operational confidence
  - leverage off commercial standards, features, and capabilities
  - interoperability over commercial networks for distributed operations
- Cons
  - overkill in many applications since the link from space to ground is a single-user link
  - protocol overhead in flight computer
  - protocol overhead on link
  - security

Networking Questions

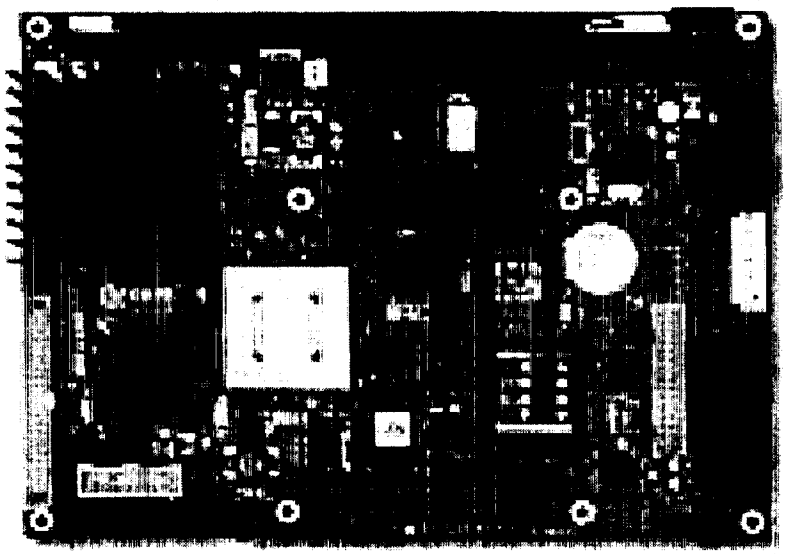
- Assumed User Profile for Small Satellite Networking
  - 2400 bps forward; < 115 kbps return
  - BER < 0.00001 on both links
  - file sizes in 1 kB through 1 MB range
  - short transfer opportunities (~ 5 minutes)
  - short propagation delays

Networking Questions

- Questions to be answered
  - is there an advantage of SCPS over TCP/IP in the satellite channel
  - do protocol options such as congestion control, header compression, etc. help performance
  - do the protocols work in limited flight computer configurations



Networking Questions



SBC with embedded Linux and networking support

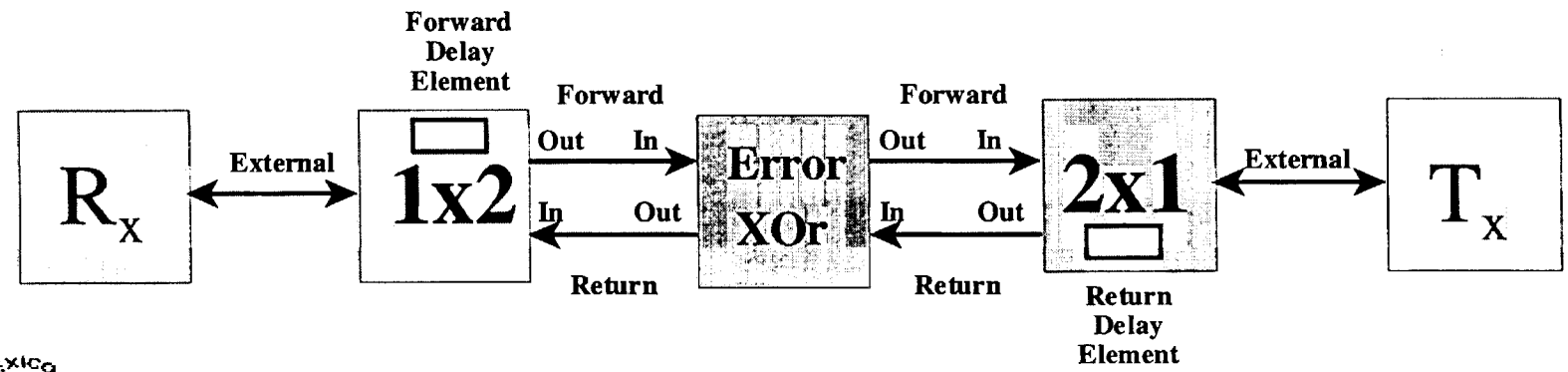
- TCP/IP
  - use commercial land lime and wireless products
  - Internet-ready single-board computers that can be used as a flight computer
  - willing to assume risk of space channel

Protocols

- Space Communications Protocol Specification (SCPS)
  - funded by NASA and DoD
  - designed around TCP/IP
  - optimized for the space channel
  - has option to treat packet loss as errors and not congestion
  - reference implementation available for Linux/Unix platforms

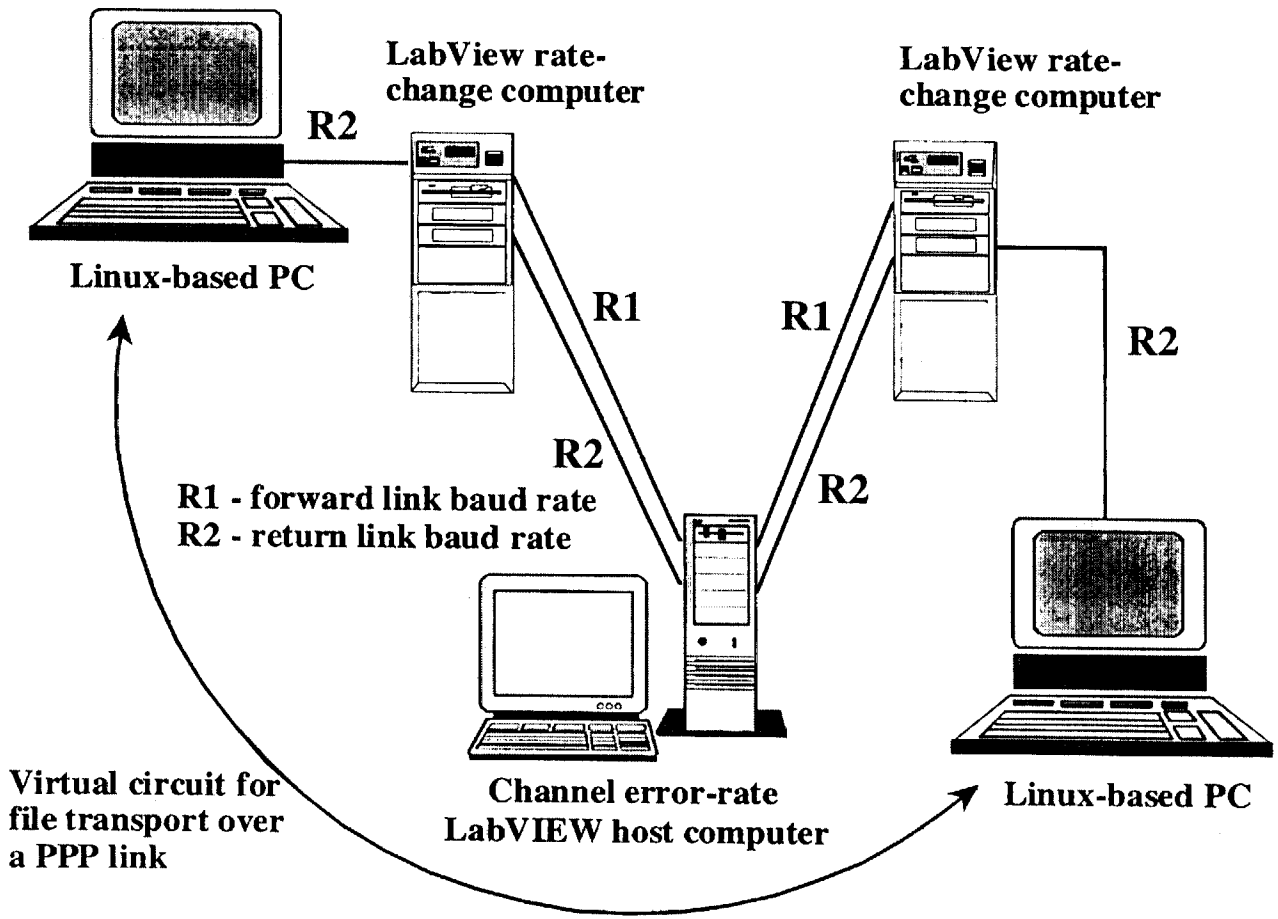
Development Efforts

- NMSU Telemetry laboratory testbed
  - model small satellite links
    - $R_b \leq 115200$ bps in each direction
    - BER selectable
    - delay < 5 seconds on each link
    - configure each link independently



Development Efforts

LabVIEW-based channel error simulator for small satellite links



Development Efforts

- Since last review
  - completed bi-directional data flow in simulator
  - added link delay up to 5 seconds
  - continued to work with MITRE on understanding SCPS reference implementation and how it interacts with operating system and link-level protocols

Development Efforts

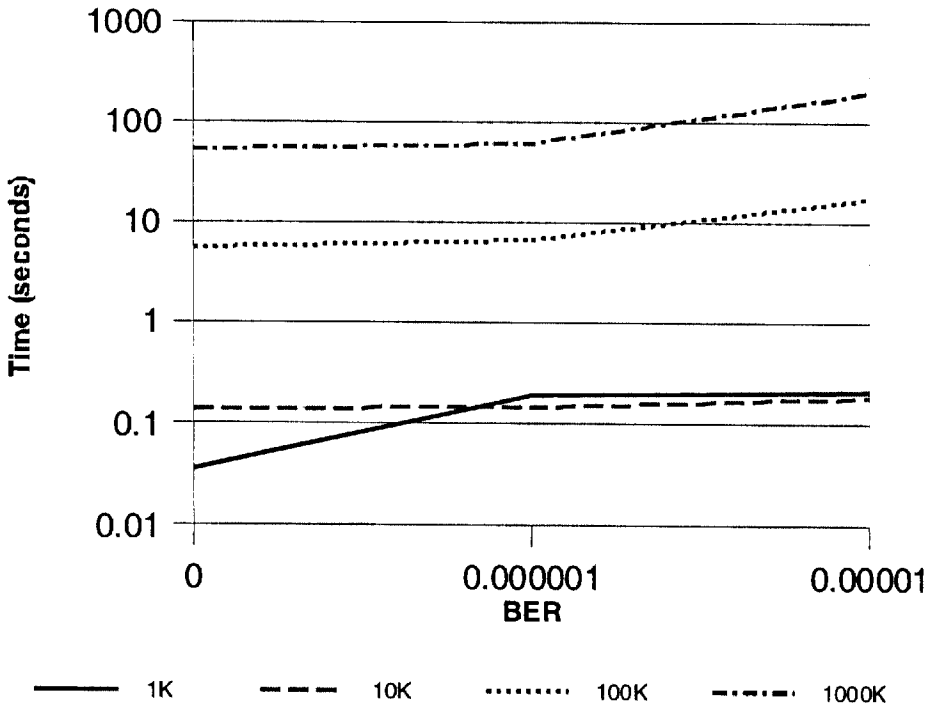
- Simulator Validation
  - MITRE spent one week here last summer working with us on validating SCPS and our simulator
  - Ran special tests to validate error generation at request of Will Ivancic @ GRC

Preliminary Results

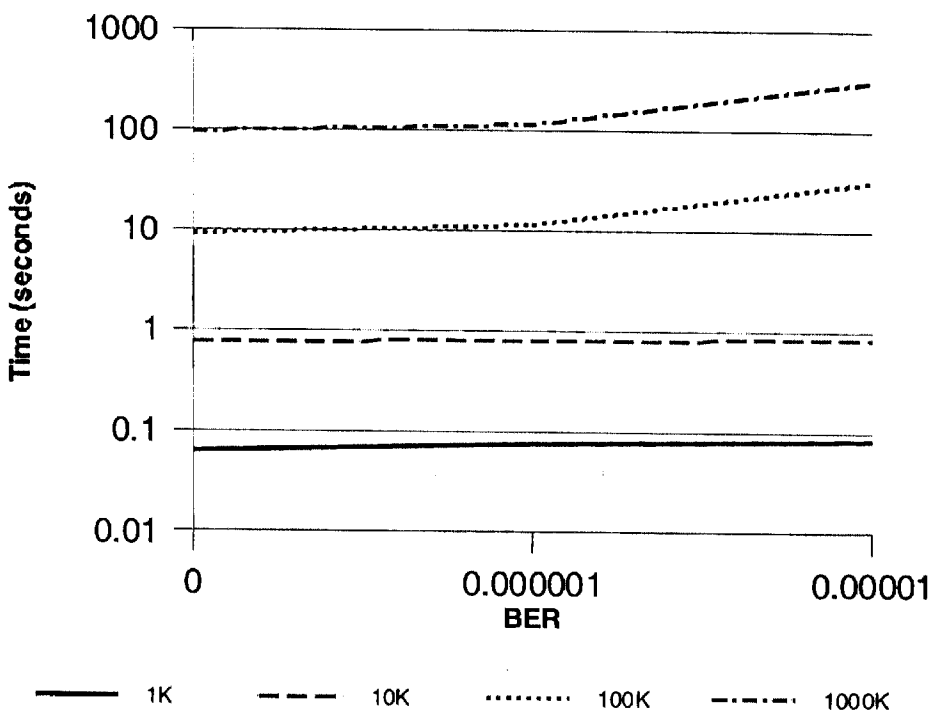
- Investigations to date
  - look at SCPS vs. TCP/IP with different congestion control modes and
    - variable link delays
    - variable BER settings
    - equal and unequal forward and return data rates
    - effects of operating system and link layer protocol on effectiveness

Preliminary Results

(a) symmetric links



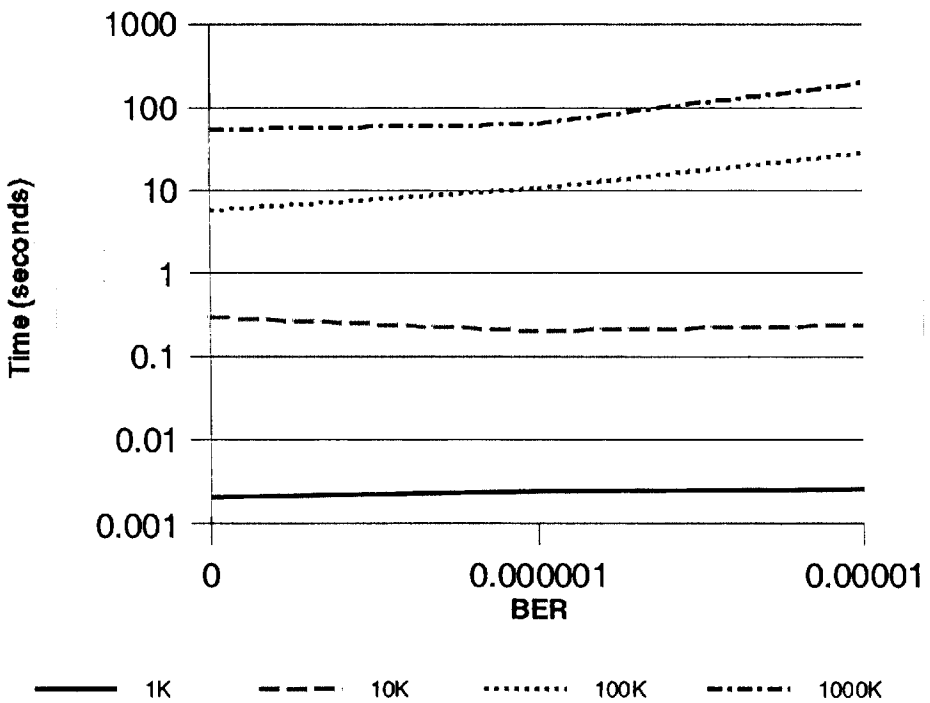
(b) unsymmetric links



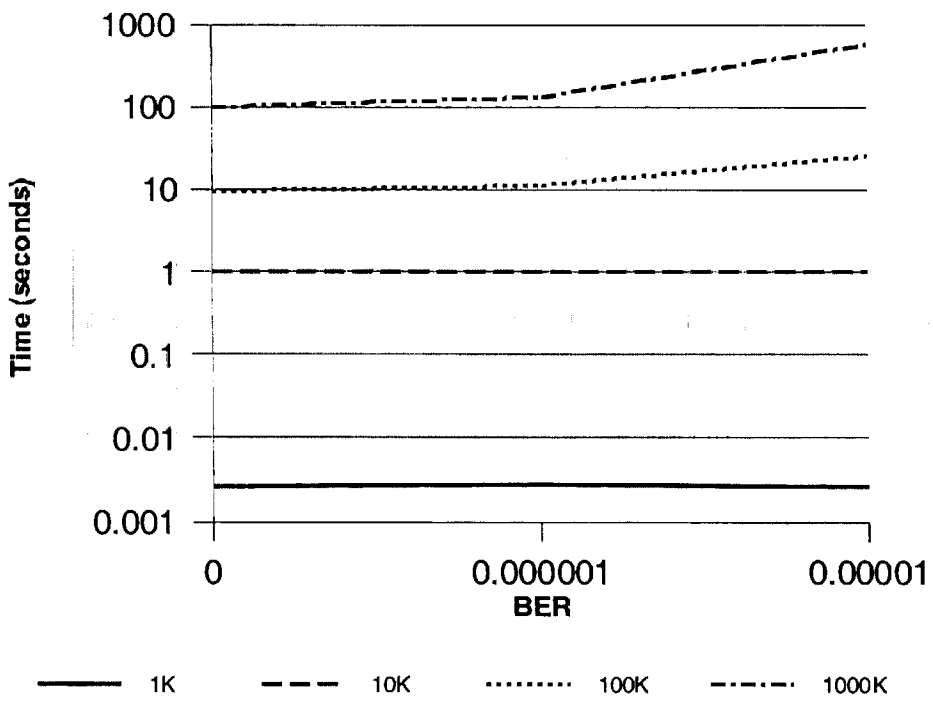
TCP/IP results as a function of file size and channel BER

Preliminary Results

(a) symmetric links



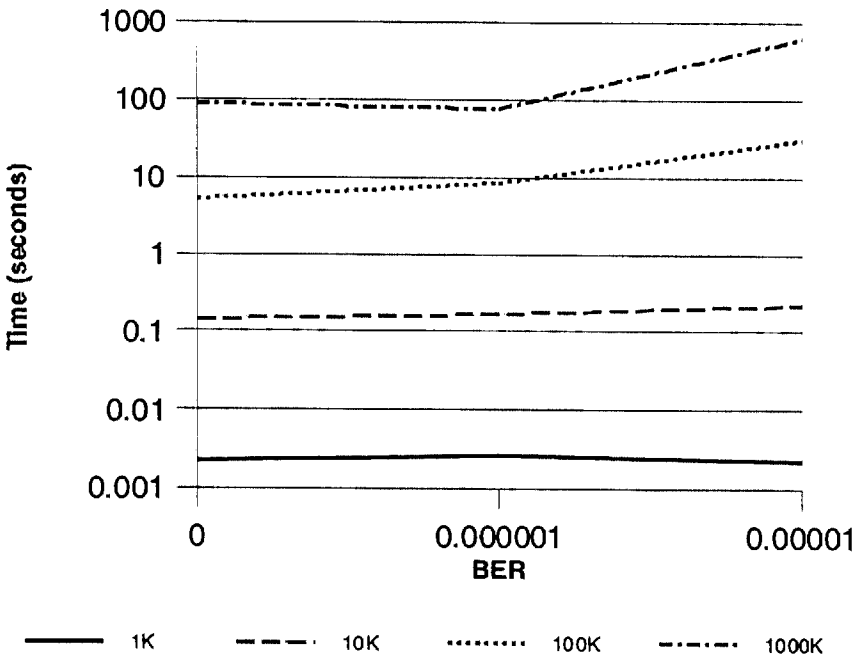
(b) unsymmetric links



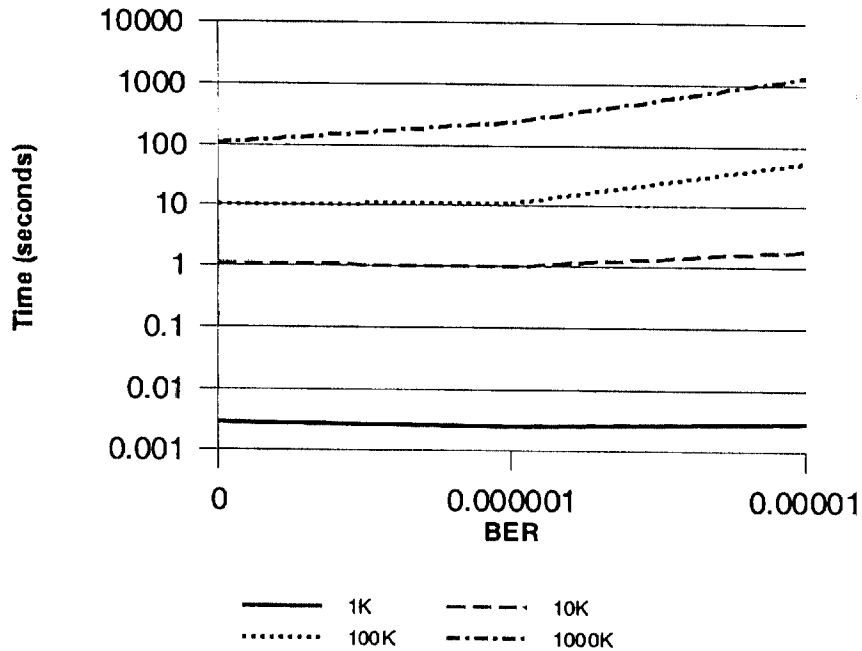
SCPS fp with VJ congestion control results as a function of file size and channel BER

Preliminary Results

(a) symmetric links



(b) unsymmetric links



SCPS fp with Vegas congestion control results as a function of file size and channel BER

Preliminary Results

- Findings to date
  - Both TCP/IP and SCPS work about the same when the channel error rate is small and both treat errors as congestion
  - Van Jacobson congestion control works a bit better than Vegas congestion control
  - No real link delay penalty for these "slow" links out to GEO orbits

Preliminary Results

- Findings to date
  - PPP does not recognize the SCPS protocol configuration so it will not support some of the internal link layer compression options. TCP can utilize these options and achieve a better throughput.

LEO Telecom Access

- Investigated the potential for small satellites to access LEO telecommunications constellations for T&C or scheduling
  - Globalstar, Iridium, Orbcom, Final Analysis investigated for orbital access and potential problems
  - Contacted all at one time for possible experiment

LEO Telecom Access

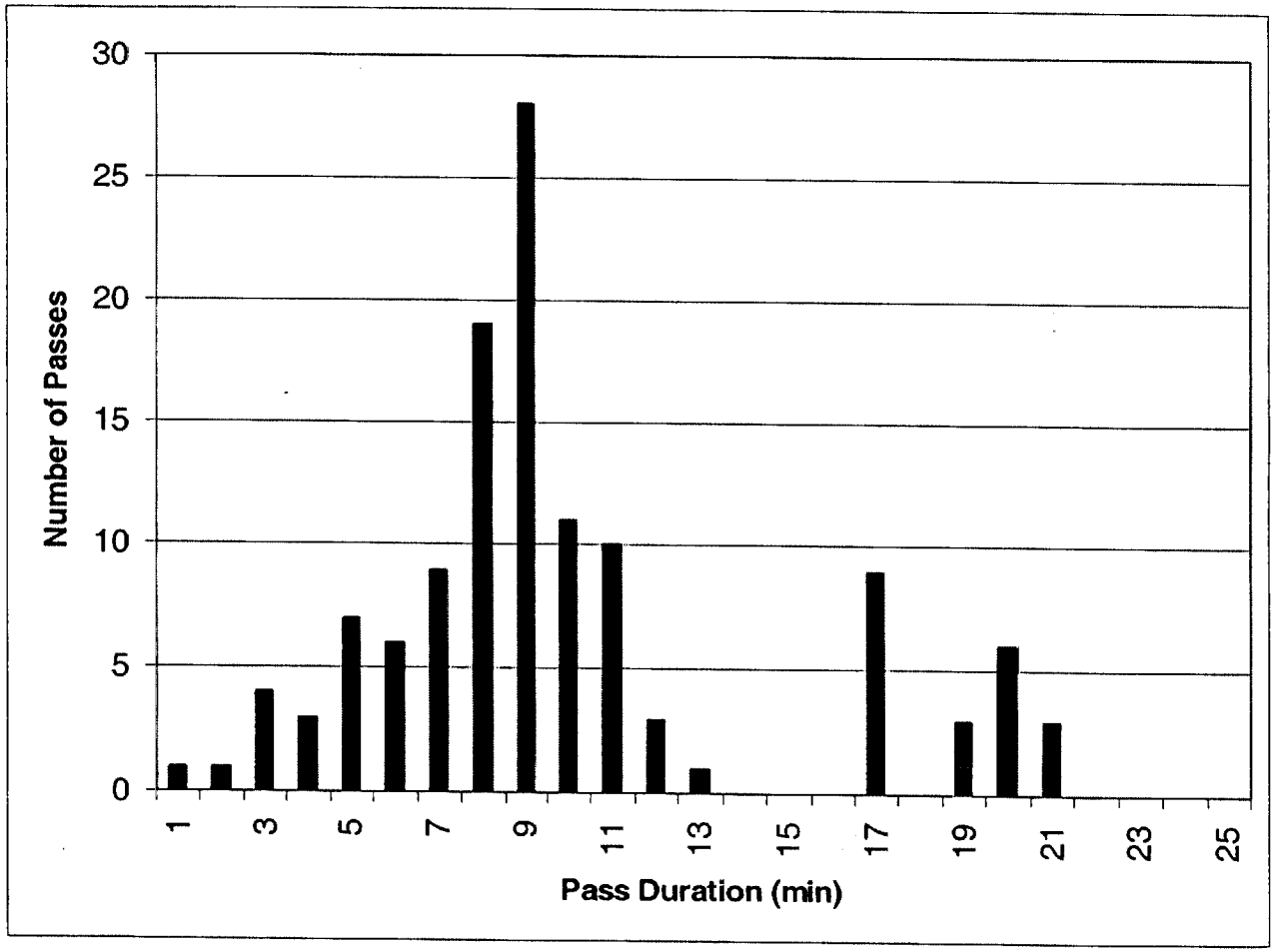
- Regulatory
  - No allocations for space-to-space services on a regular basis for LEO satellites and telecommunications communications satellites
  - For now, we will assume that this is an issue that can eventually be worked out

LEO Telecom Access

- Initial Proposal
  - Look at Iridium to service 3 Corner Satellite
- Constellations Used in the Analysis
  - Globalstar
  - Orbcomm
- Alternative Constellation
  - Final Analysis

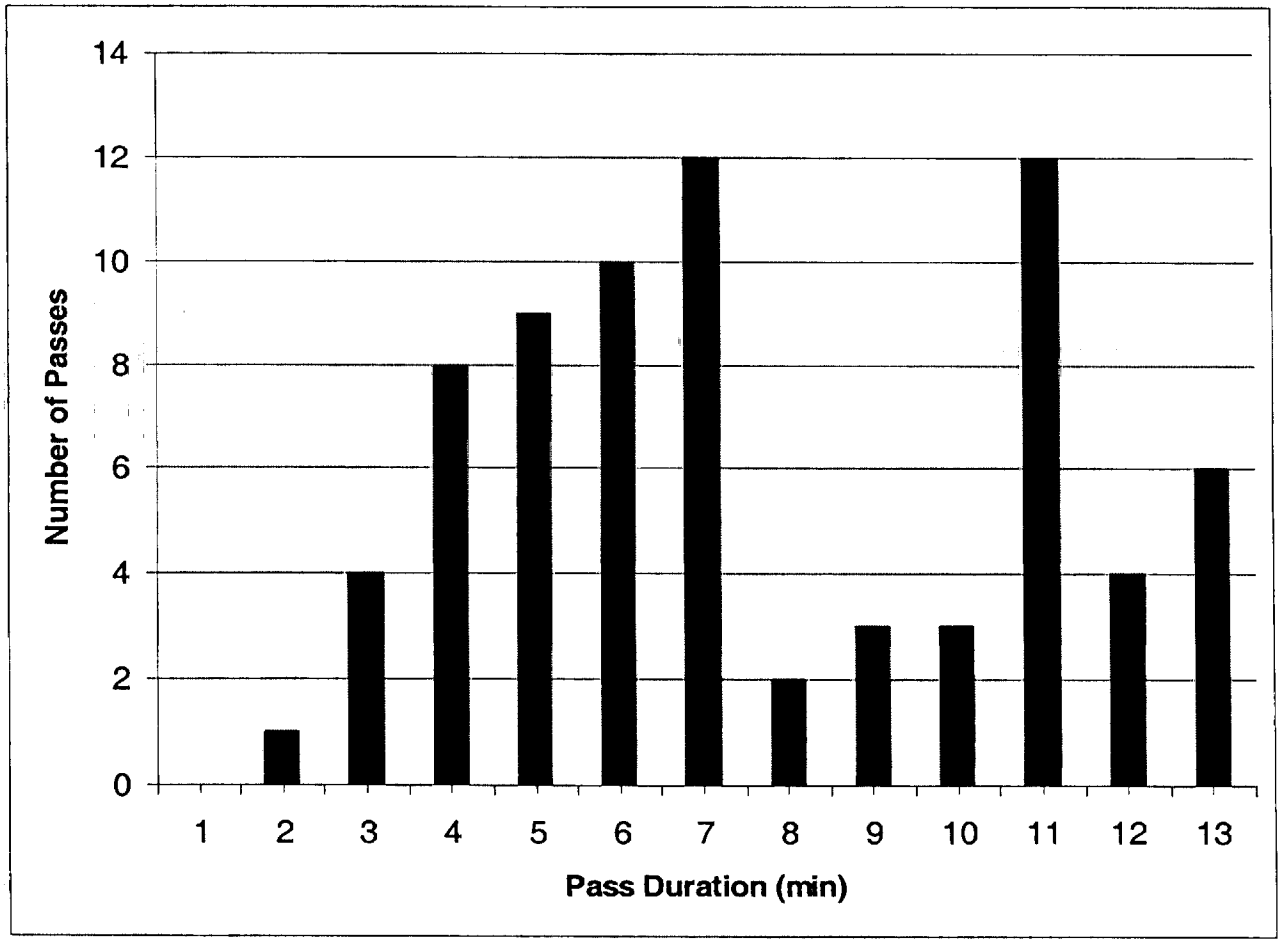
LEO Telecom Access

- Globalstar Access
  - 350 km alt.
  - 28.5° inclin.



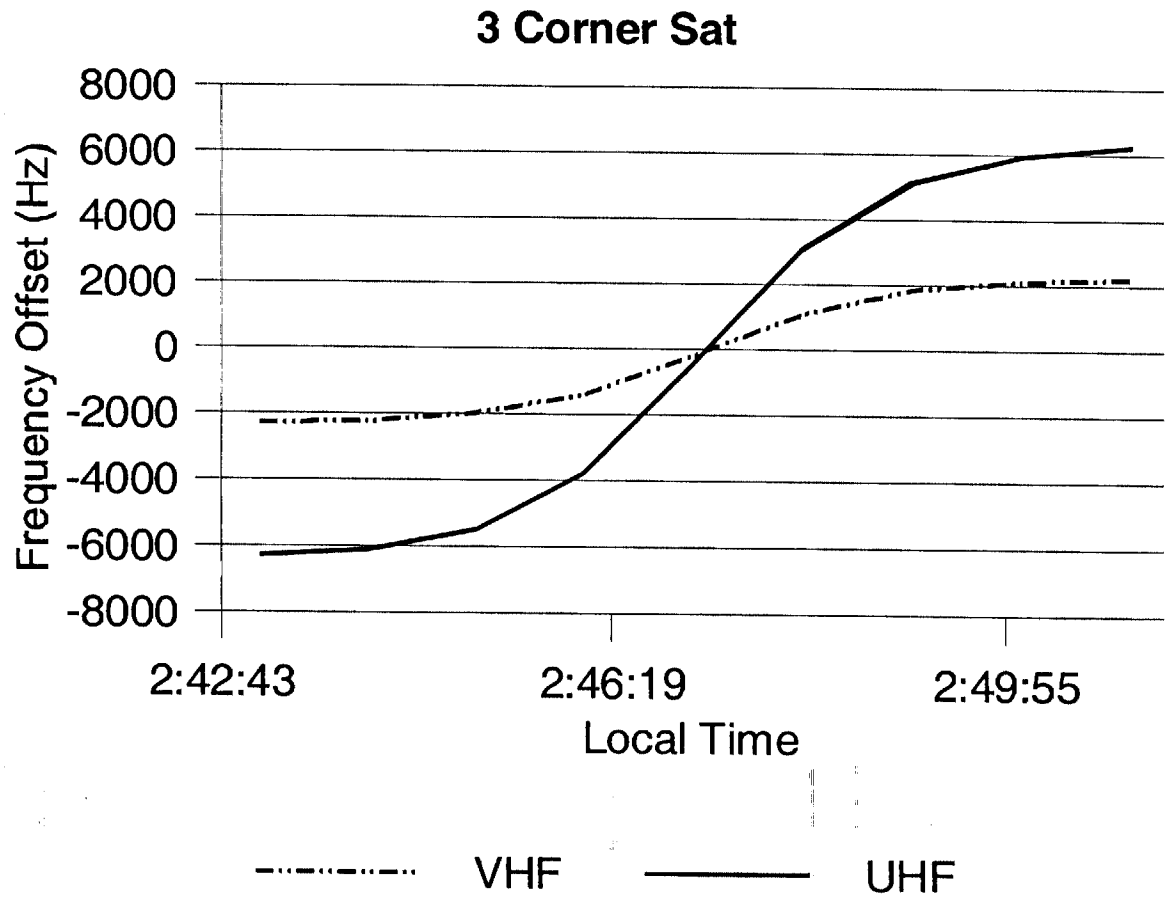
LEO Telecom Access

- Orbcomm Access
  - 350 km alt.
  - 28.5° inclin.



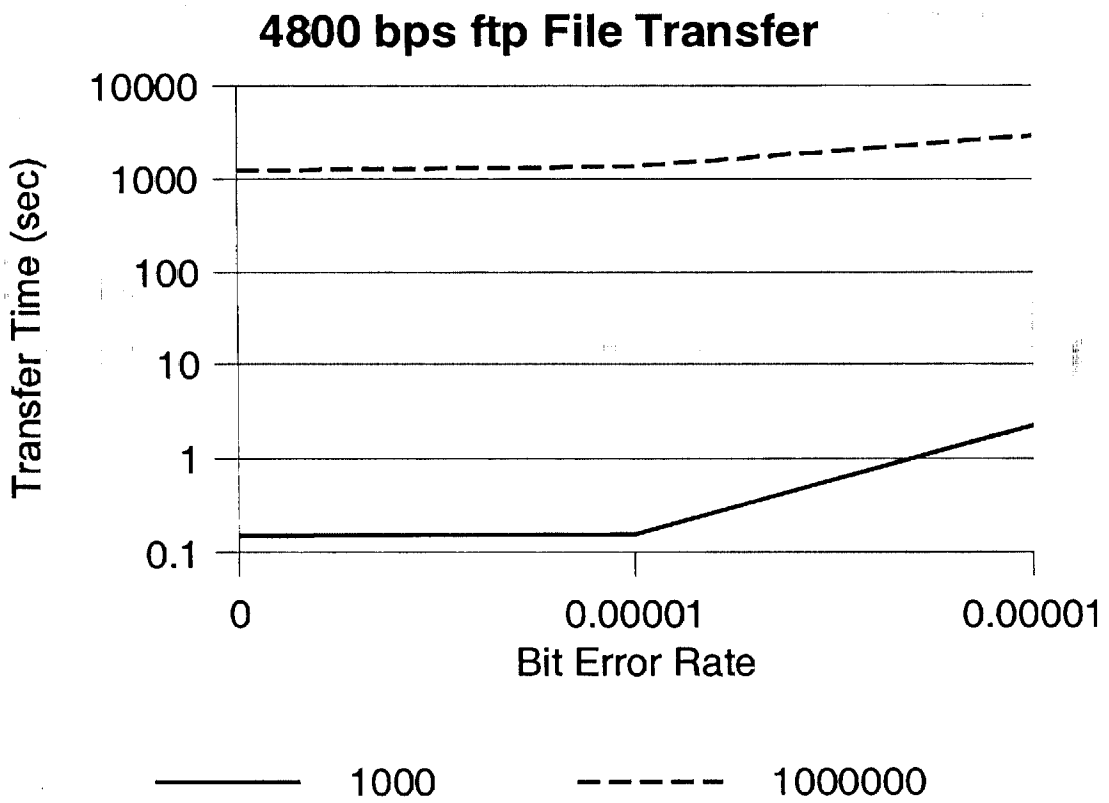
LEO Telecom Access

- Orbcomm Doppler Shifts



LEO Telecom Access

- File transfer times for 1 kB and 1 MB files over PPP link

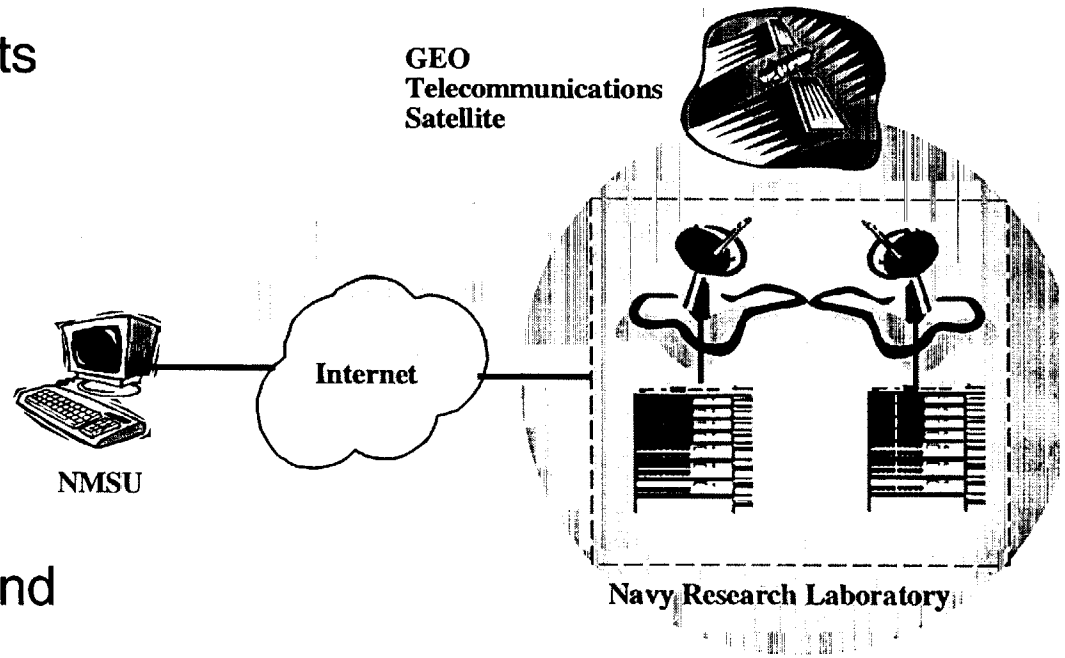


Next Steps

- In-lab tests
  - conduct tests of SCPS reference implementation with lost packets treated as errors and not congestion
    - measure any advantage over standard TCP which still treats errors as congestion
  - Upgrade simulator to 921600 bps on each link

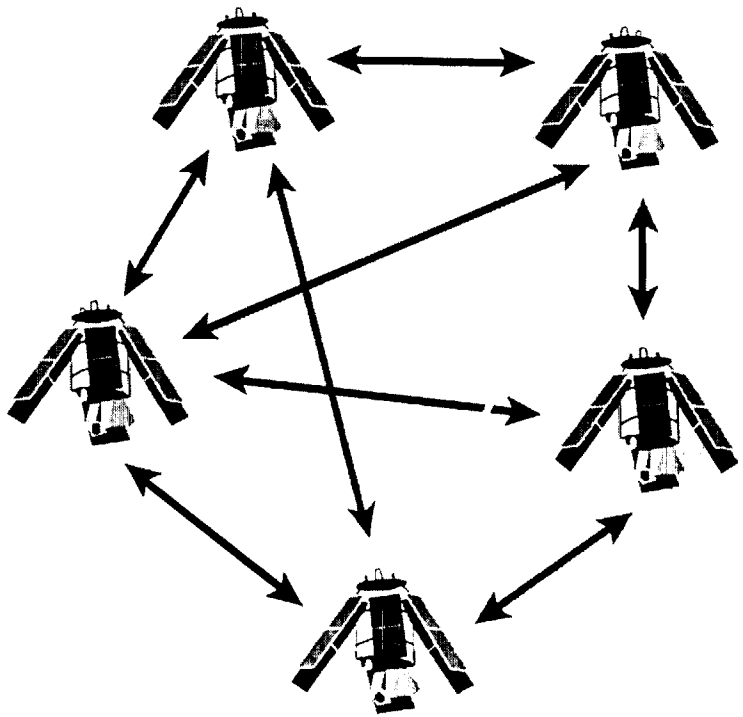
Next Steps

- Satellite Tests
  - validate simulator results over a satellite link at Navy Research Laboratory
  - investigate > 1 Mbps response of TCP and SCPS
  - investigate SCPS with loss treated as errors and not congestion



Future Possibilities

- Satellite Clusters (Formation Flying)
  - Needs a method to interconnect satellites without prior synchronization
  - Need to allow clusters to grow and shrink
  - Base technology on something like the upcoming Bluetooth or wireless LAN standards



Future Possibilities

- Many unanswered questions related to access security, data integrity, data distribution
- There are regulatory and engineering issues involved with accessing LEO telecommunications from LEO satellites for T&C and scheduling communications

Future Possibilities

- Integrating the satellite with the wireless industry is an exciting concept if regulatory problems can be overcome
- Terrestrial wireless technology may provide a good road map for formation flying development
- Internet world will be a big help in addressing protocol issues

Recent Results on Coding and Nonlinear Equalization at the University of Arizona

William Ryan

University of Arizona

March 8, 2001

Outline

- early turbo code designs (serial and parallel)
- more recent turbo code designs: double turbo DPSK
- initial work on low-density parity-check codes
- combined nonlinear equalization and decoding

Bandwidth-Efficient Parallel and Serial Concatenated Codes for QPSK Modulation:

Consideration for the CCSDS Near-Earth Standard

William E. Ryan, University of Arizona

Omer Acikel, New Mexico State University

March 4, 2001

OUTLINE

- Bandwidth-efficient signaling with MPSK
- The proposed codes - parallel and serial concatenations
- Performance results for the codes

BANDWIDTH-EFFICIENT SIGNALING

- bandwidth-efficiency for coded QPSK (r = code rate):

$$\mathcal{E}_{QPSK,\text{ coded}} = 2r \text{ (bits/sec)/Hz}$$

- bandwidth-efficiency for coded 8PSK (r = code rate):

$$\mathcal{E}_{8PSK,\text{ coded}} = 3r \text{ (bits/sec)/Hz}$$

Example

- rate 2/3 trellis coded 8PSK:

$$\mathcal{E}_{8PSK,\text{ coded}} = 2 \text{ (bits/sec)/Hz}$$

- rate 15/16 turbo coded QPSK:

$$\mathcal{E}_{QPSK,\text{ coded}} = 1.875 \text{ (bits/sec)/Hz}$$

- but, the coded QPSK scheme is more power efficient and has a more robust receiver

THE PROPOSED CODES

The Parallel Concatenated Convolutional Codes

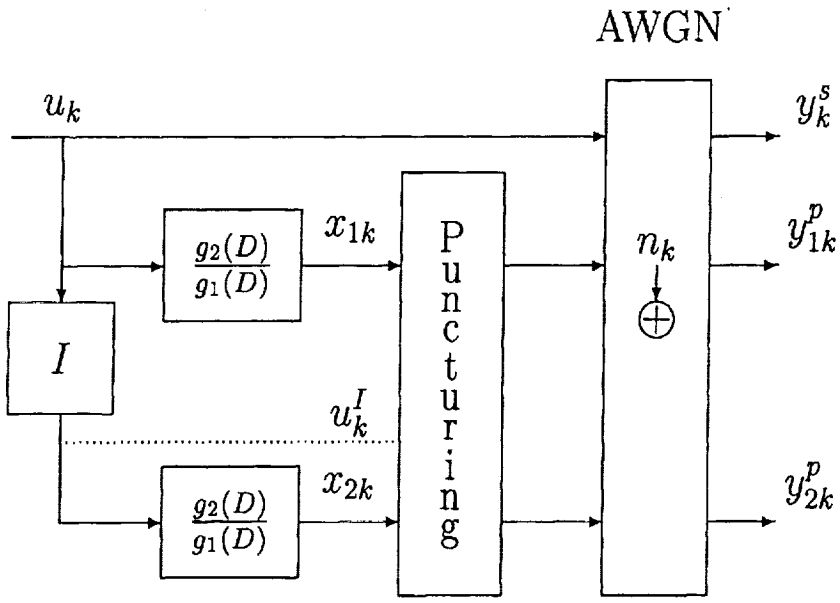
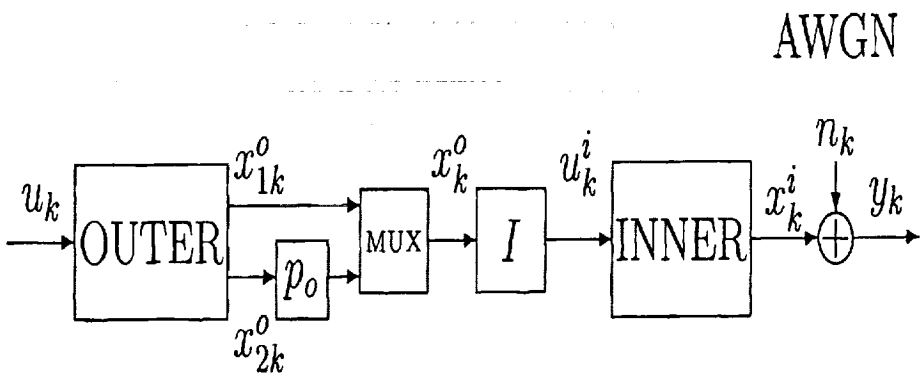


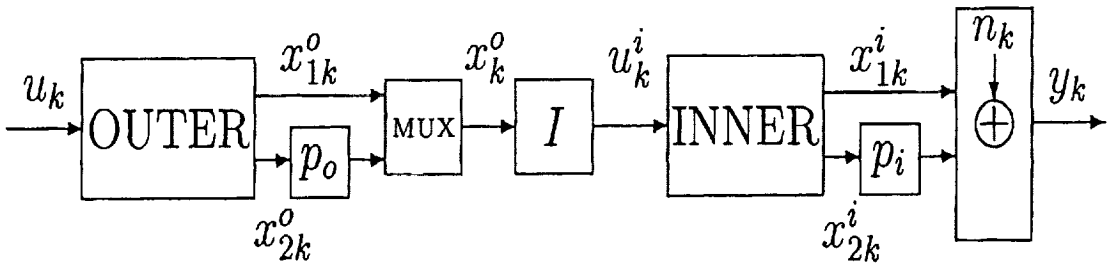
Diagram of PCCC encoder.

- we consider rate 3/4, 7/8, and 15/16 PCCCs, with memory $m =$ 3 component recursive systematic convolutional codes

The Serial Concatenated Convolutional Codes



SCCC encoder with differential encoder as rate 1 inner code.



SCCC encoder with two rate 1/2 RSC encoders.

(1) **Top Diagram**: a punctured outer rate $r_o = k/(k+1)$ RSC encoder and a $r_i = 1$ (2-state) differential encoder

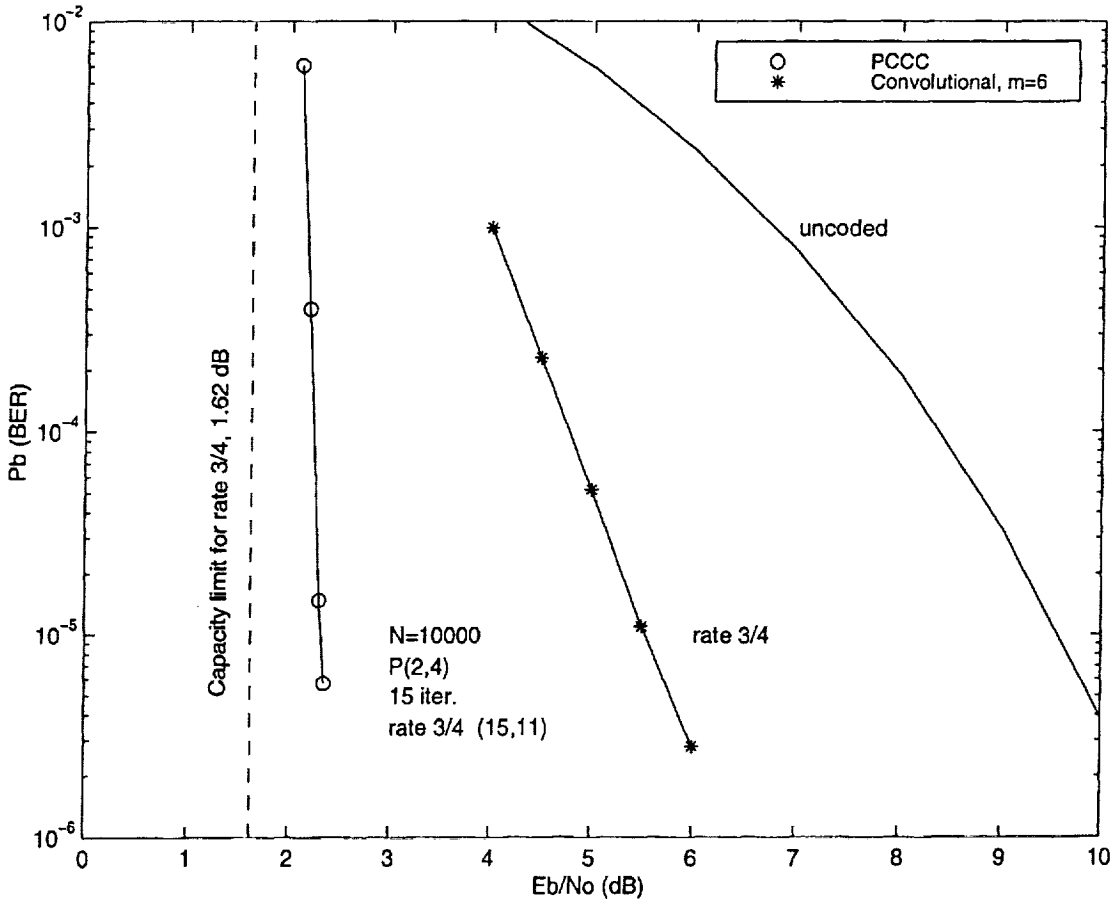
(2) **Bottom Diagram**: two $m = 3$ RSC encoders, with the inner and outer RSCs punctured to achieve rates $r_i = 2k/(2k+1)$ and $r_o = (2k+1)/(2k+2)$, respectively

- We consider rate 3/4, 7/8, and 15/16 SCCCs.

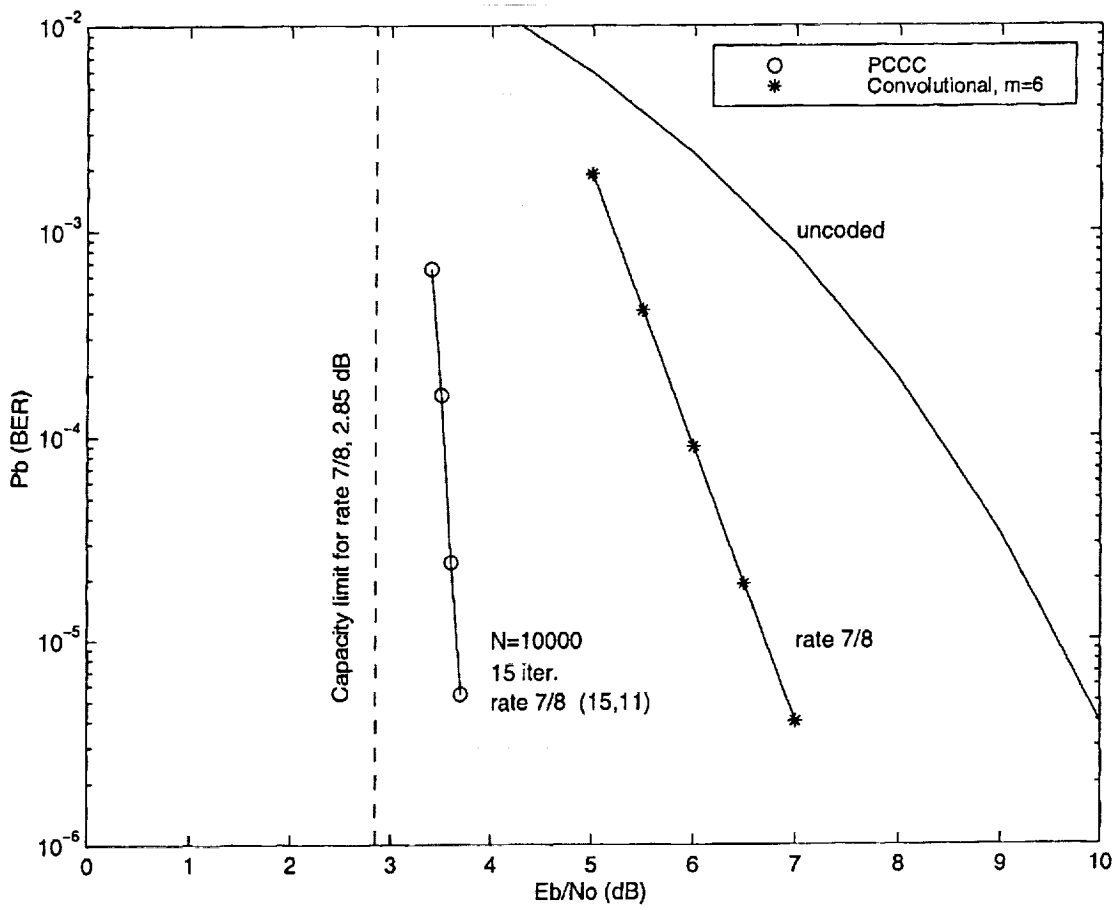
PERFORMANCE RESULTS

PCCC Performance

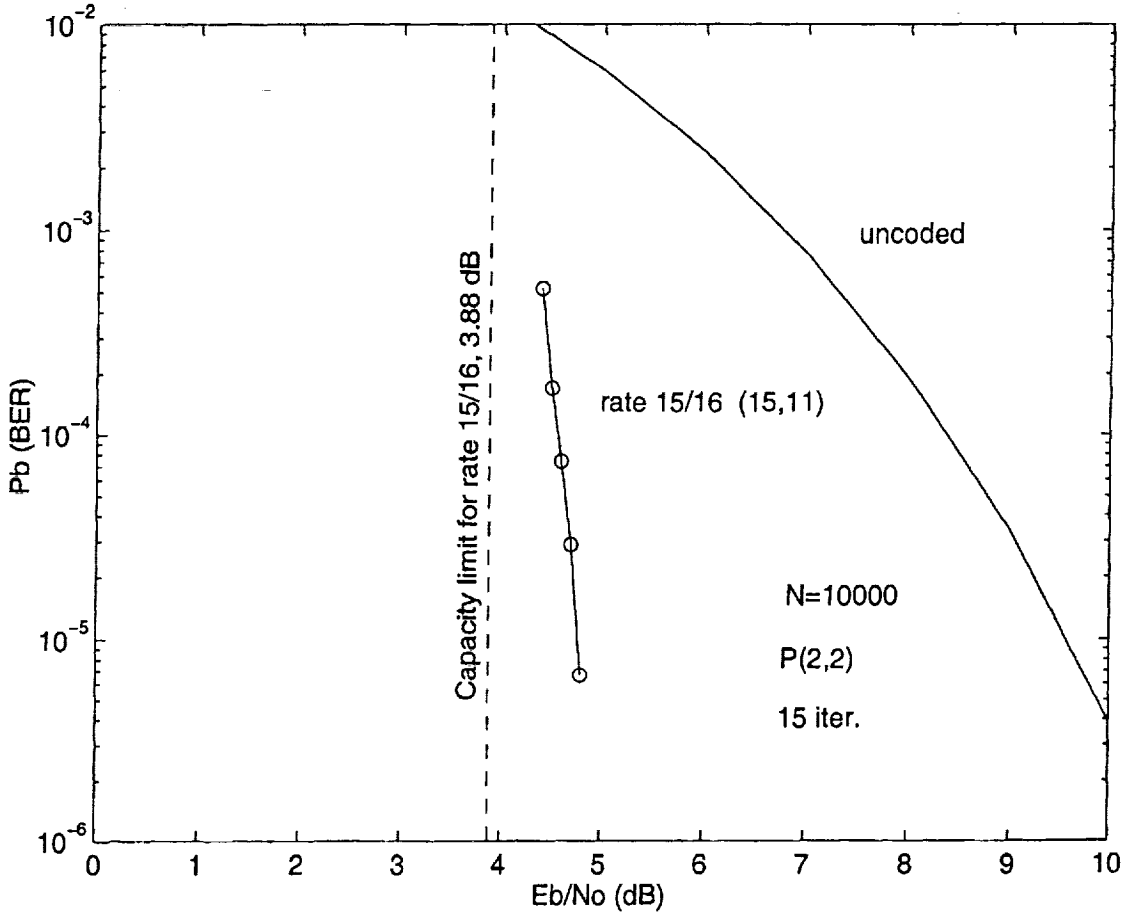
- decoder: iterative BCJR-APP algorithm with 15 iterations
- information word size: 10,000 bits
- code rates: 3/4, 7/8, and 15/16



Rate 3/4 PCCC bit error rate performance.



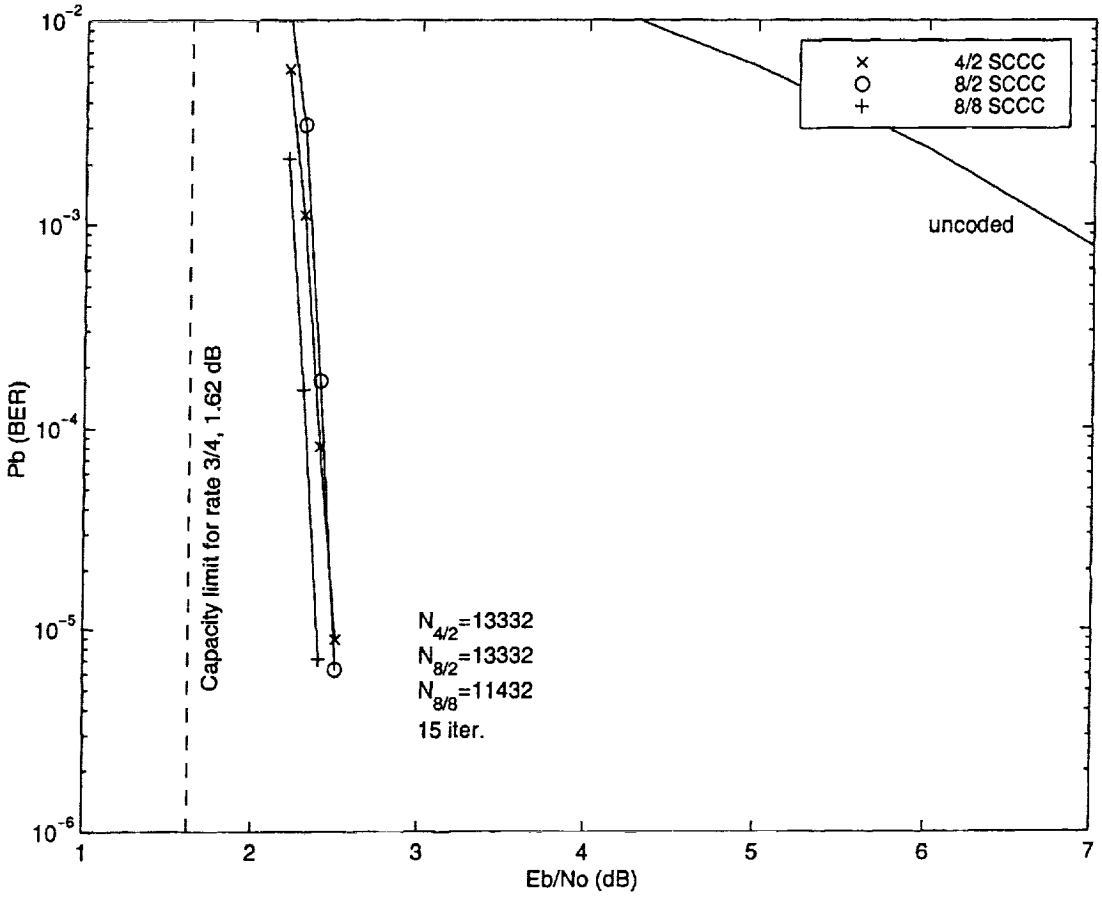
Rate 7/8 PCCC bit error rate performance.



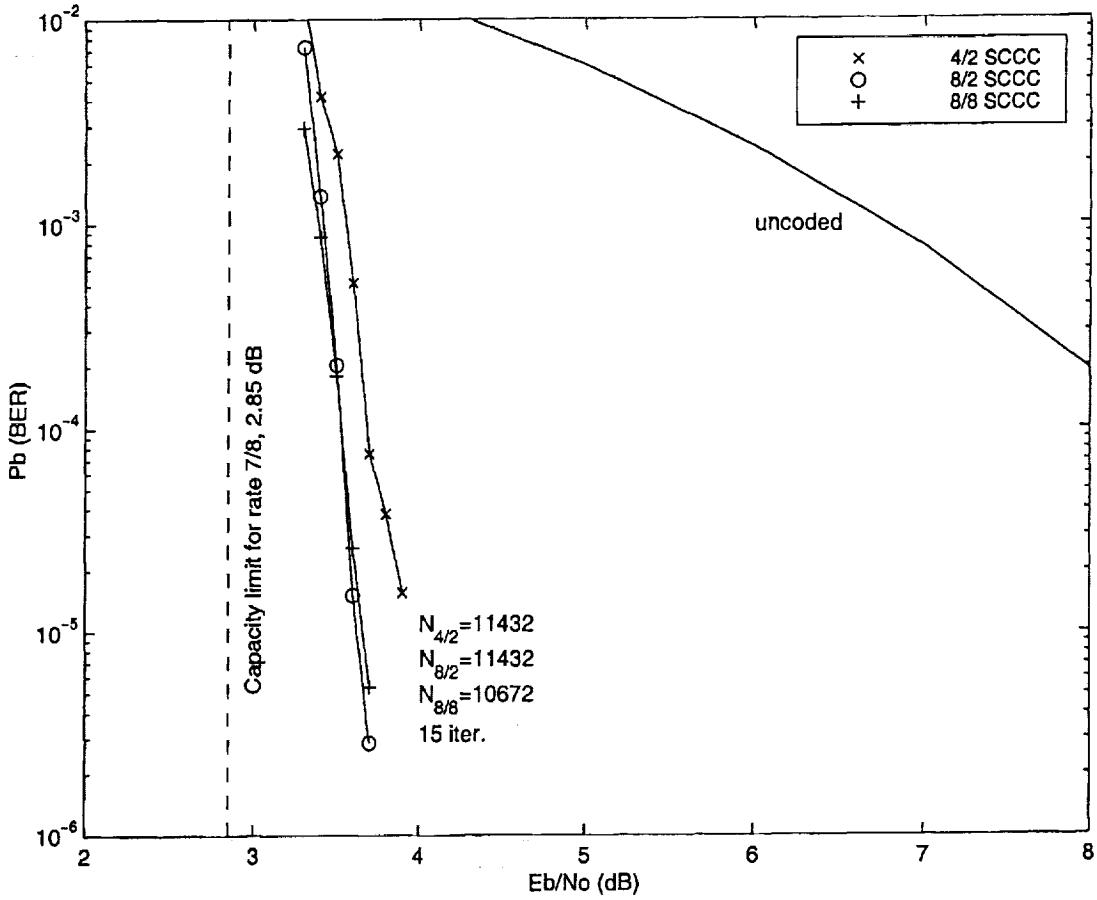
Rate 15/16 PCCC bit error rate performance.

SCCC Performance

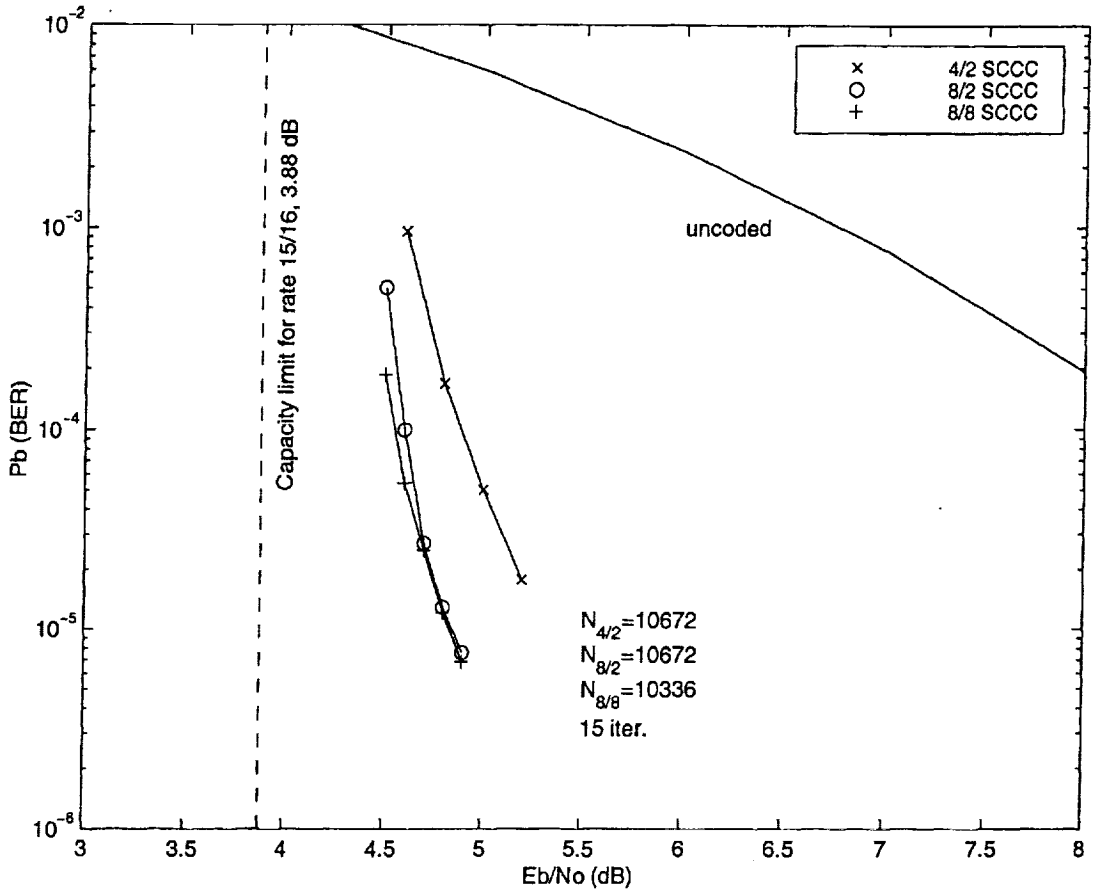
- decoder: iterative BCJR-SISO algorithm with 15 iterations
- information word size: 10,000 bits
- code rates: 3/4, 7/8, and 15/16



Rate 3/4 SCCC bit error rate performance.

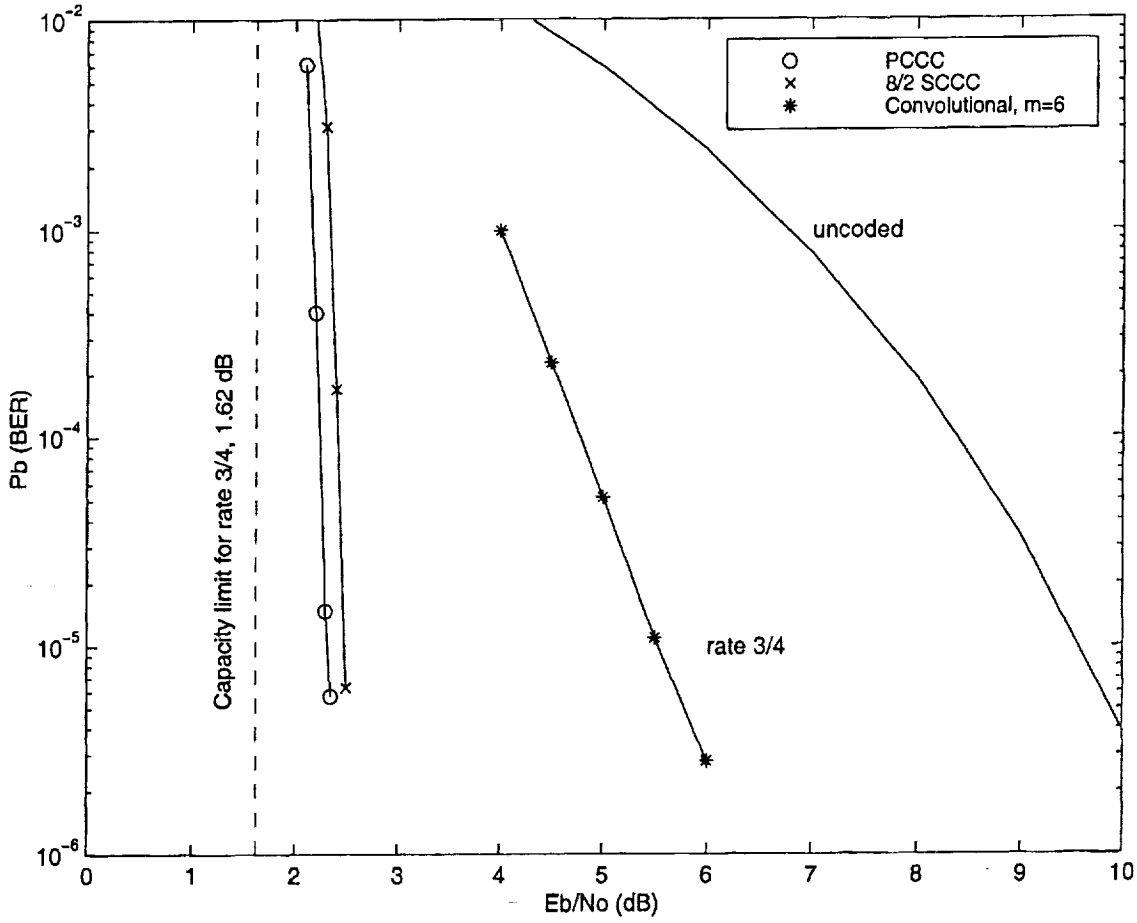


Rate 7/8 SCCC bit error rate performance.

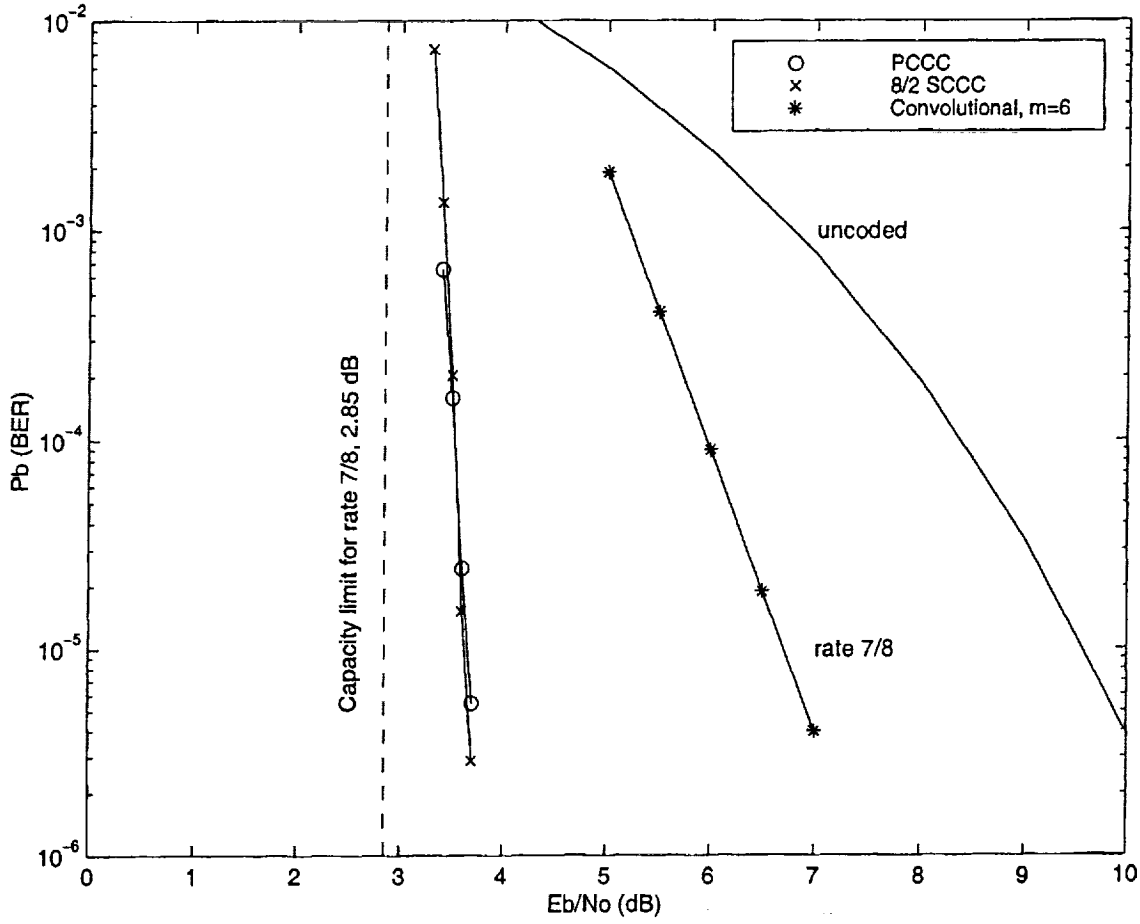


Rate 15/16 SCCC bit error rate performance.

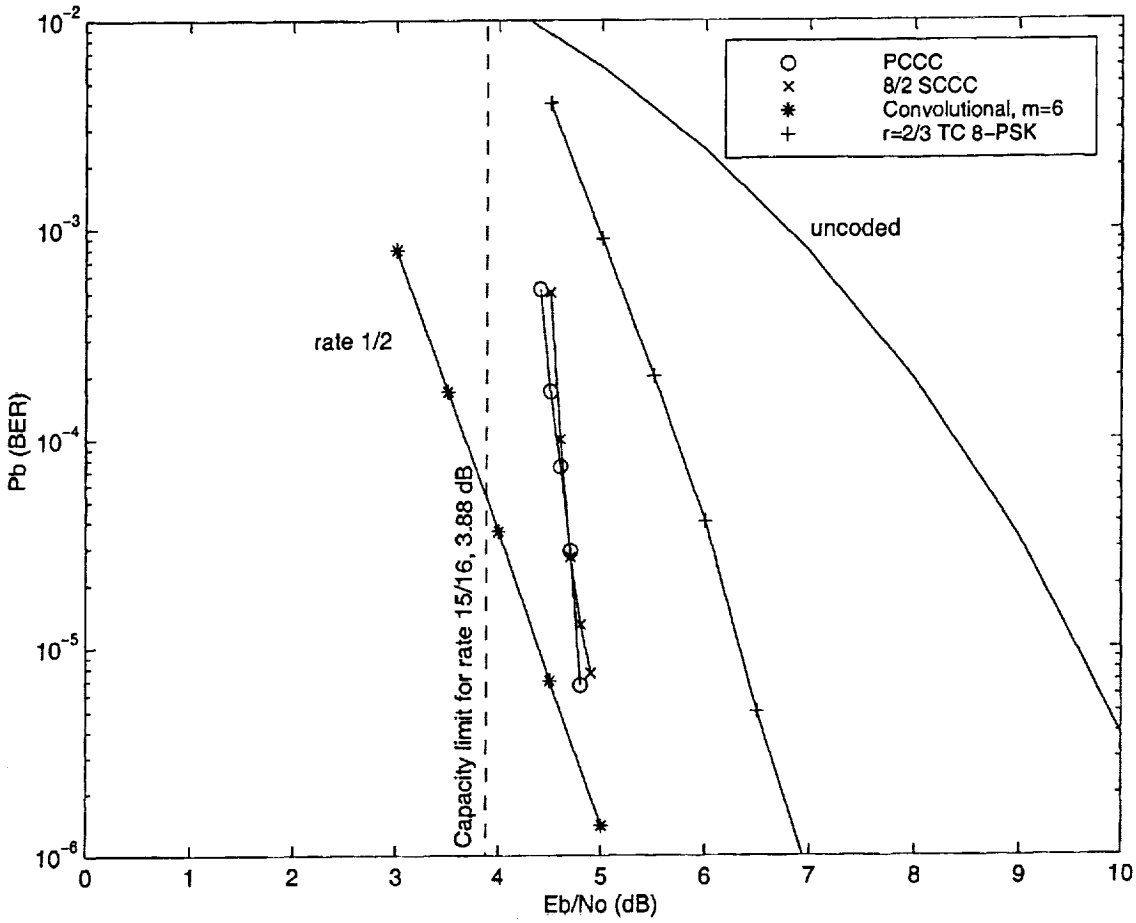
Performance Comparisons: PCCC, SCCC, Convolutional, and Trellis-Coded 8-PSK



Comparision of rate 3/4 codes: PCCC, 8/2 SCCC, and a memory 6 convolutional code.



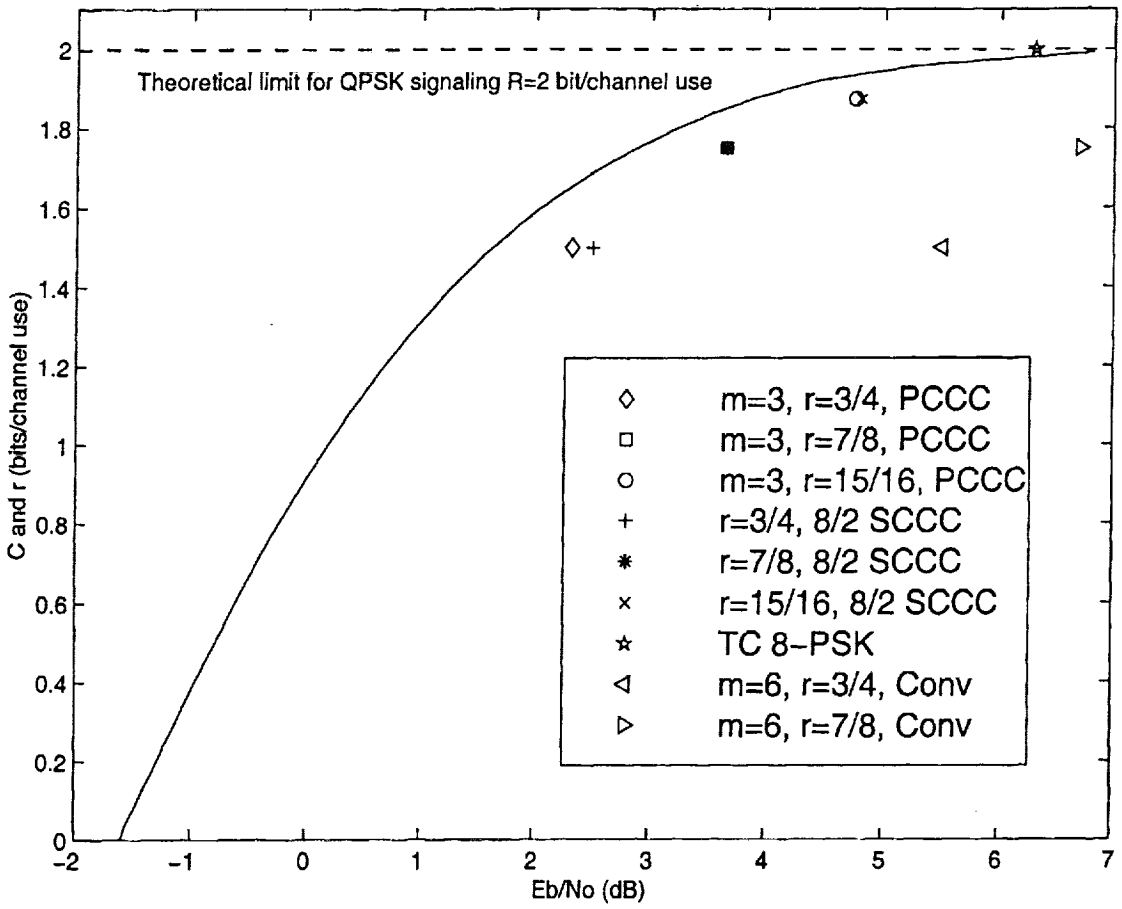
Comparision of rate 7/8 codes: PCCC, 8/2 SCCC, and a memory 6 convolutional code.



Comparision of the rate 15/16 PCCC and 8/2 SCCC codes, and rate 2/3 trellis-coded 8PSK.

Comparison to QPSK Capacity Curve

- the E_b/N_0 required to achieve a bit error rate of 10^{-5} is plotted against the QPSK capacity curve

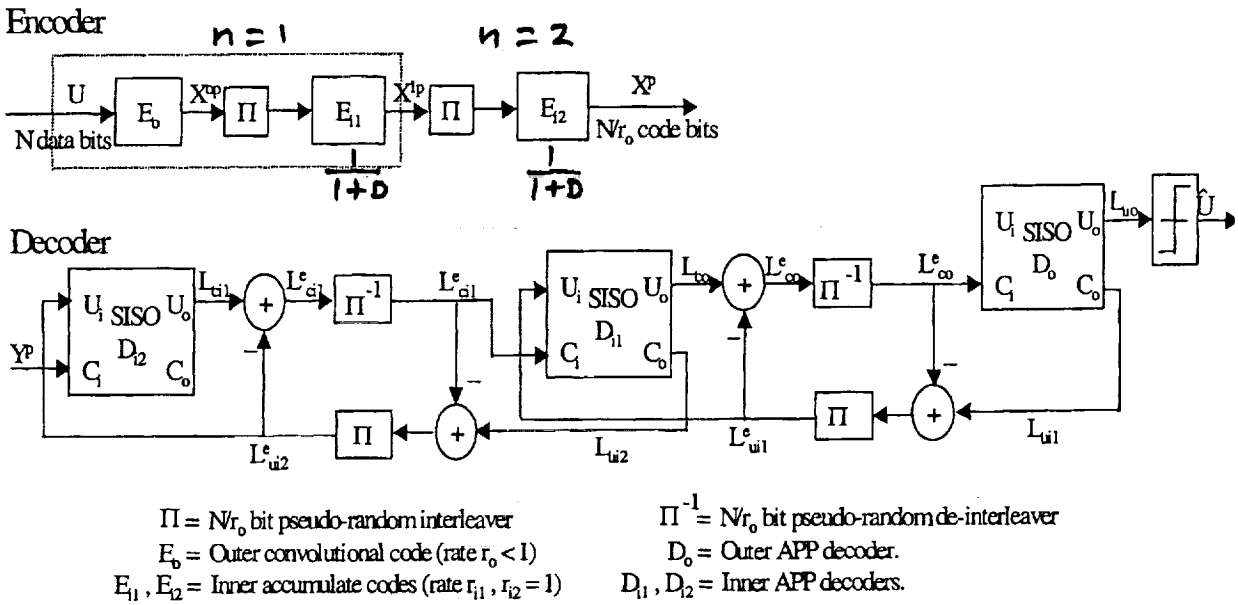


Bandwidth-/Power-Efficiency operating points for the codes presented in this paper.

Convolutional Double Accumulate Codes (or Double Turbo DPSK)

Rajeev Ramamurthy and William E. Ryan
ECE Department, University of Arizona

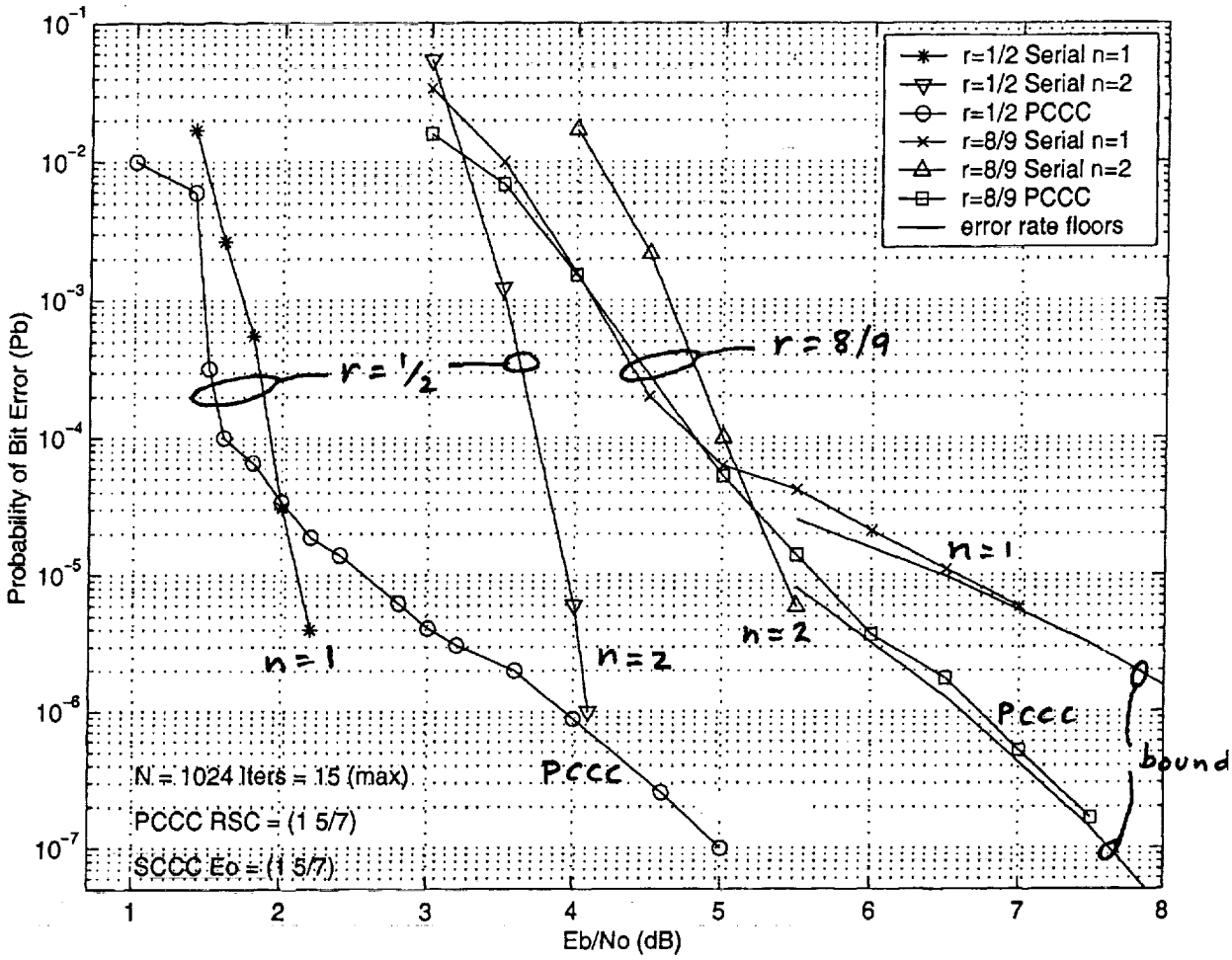
November 15, 2000



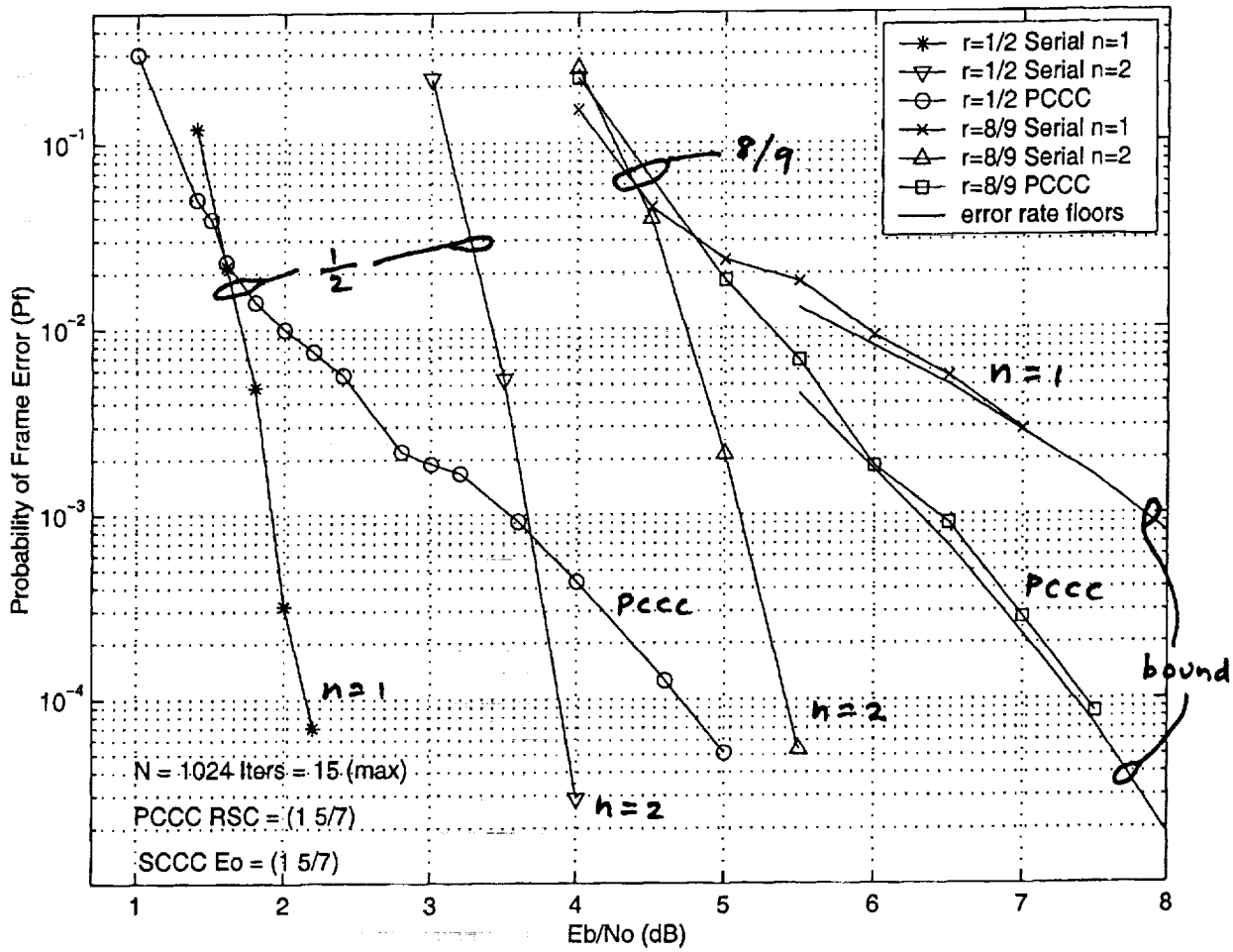
Π = N/r_0 bit pseudo-random interleaver
E_0 = Outer convolutional code (rate $r_0 < 1$)
E_{i1} , E_{i2} = Inner accumulate codes (rate r_{i1} , $r_{i2} = 1$)

Π^{-1} = N/r_0 bit pseudo-random de-interleaver
D_o = Outer APP decoder.
D_{i1} , D_{i2} = Inner APP decoders.

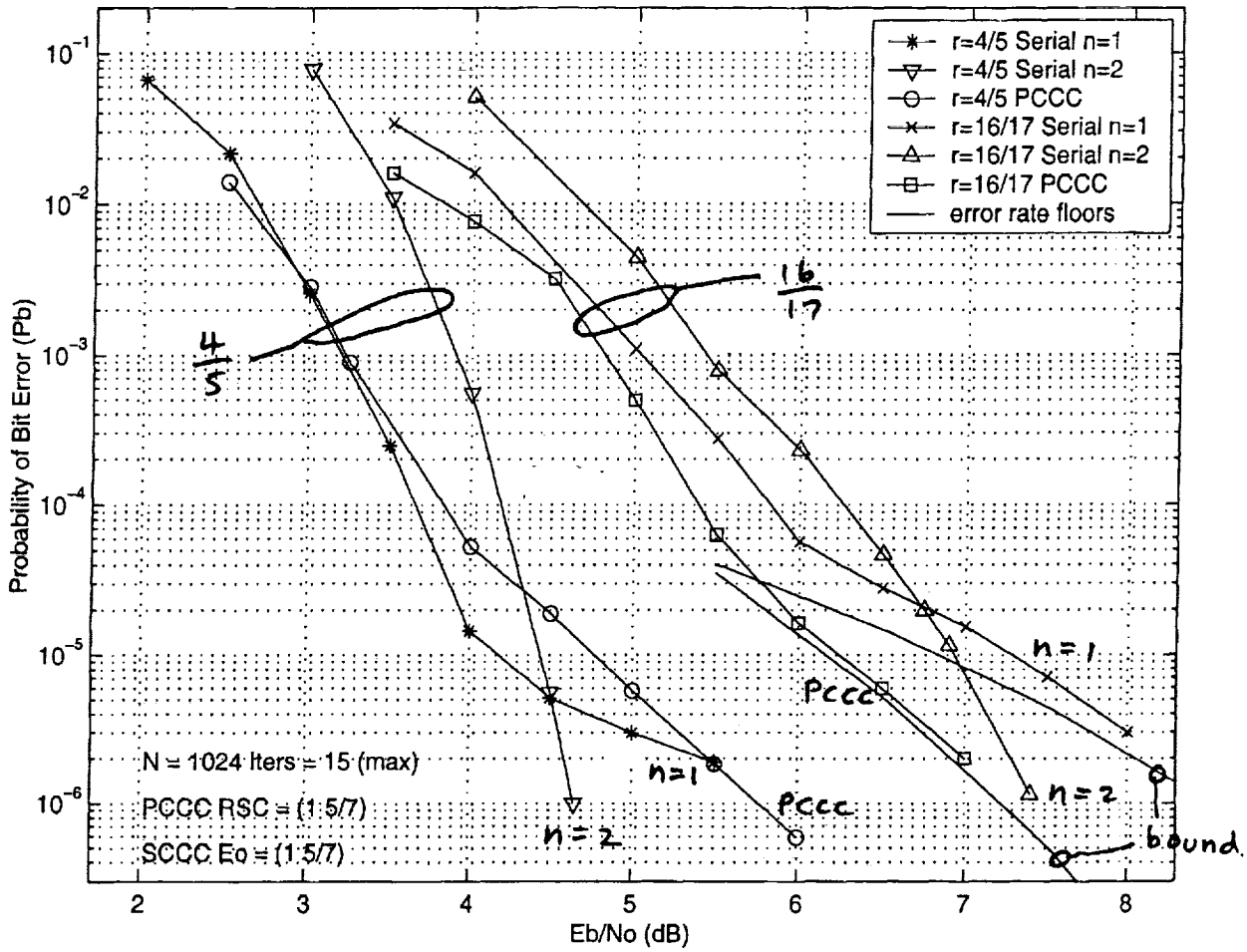
Encoder and decoder for double turbo DPSK.



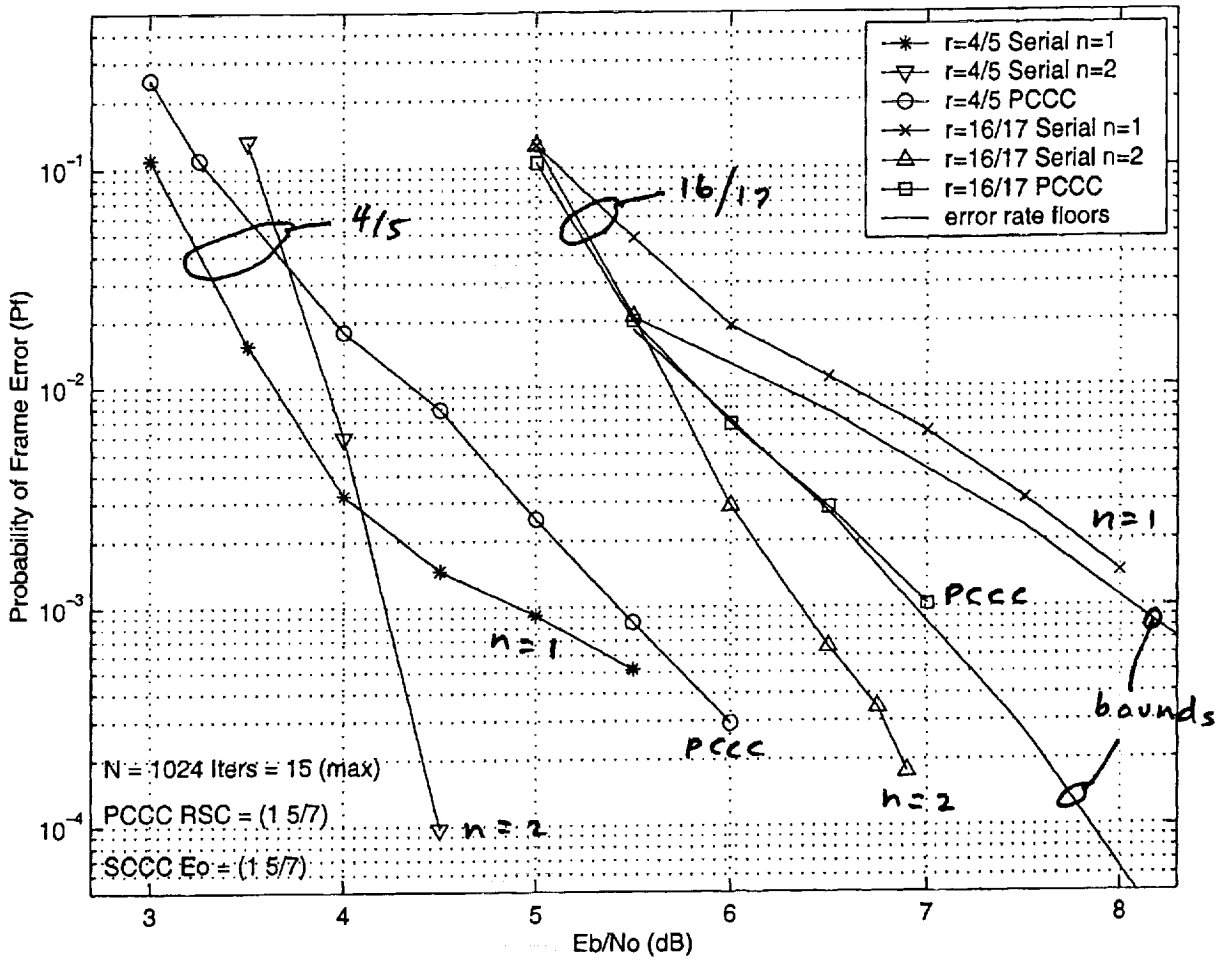
BER's of rate $\frac{1}{2}$ and $\frac{8}{9}$ serial and parallel codes.



FER's of rate $\frac{1}{2}$, $\frac{8}{9}$ serial, parallel codes.



BER's of rate $\frac{4}{5}$ and $\frac{16}{17}$ serial and parallel codes.



FER's of rate $\frac{4}{5}$, $\frac{16}{17}$ serial, parallel codes.

Initial Results on Low-Density Parity-Check Codes

Michael Yang and William Ryan
University of Arizona

March 2001

- low-density parity-check codes were invented by Gallager circa 1960 at MIT for his doctoral dissertation

- approximately five years ago, they were independently re-invented by MacKay (Cambridge University) and others

- the idea behind these codes (we assume binary codes):

    1. recall all codewords in a linear code form the nullspace of a so-called parity-check matrix **H**:

        $\mathbf{Hc}^T = \mathbf{0}$ whenever **c** is a codeword

    2. we say the binary matrix **H** is low-density if it is sparse, that is, if it contains only a small fraction of ones

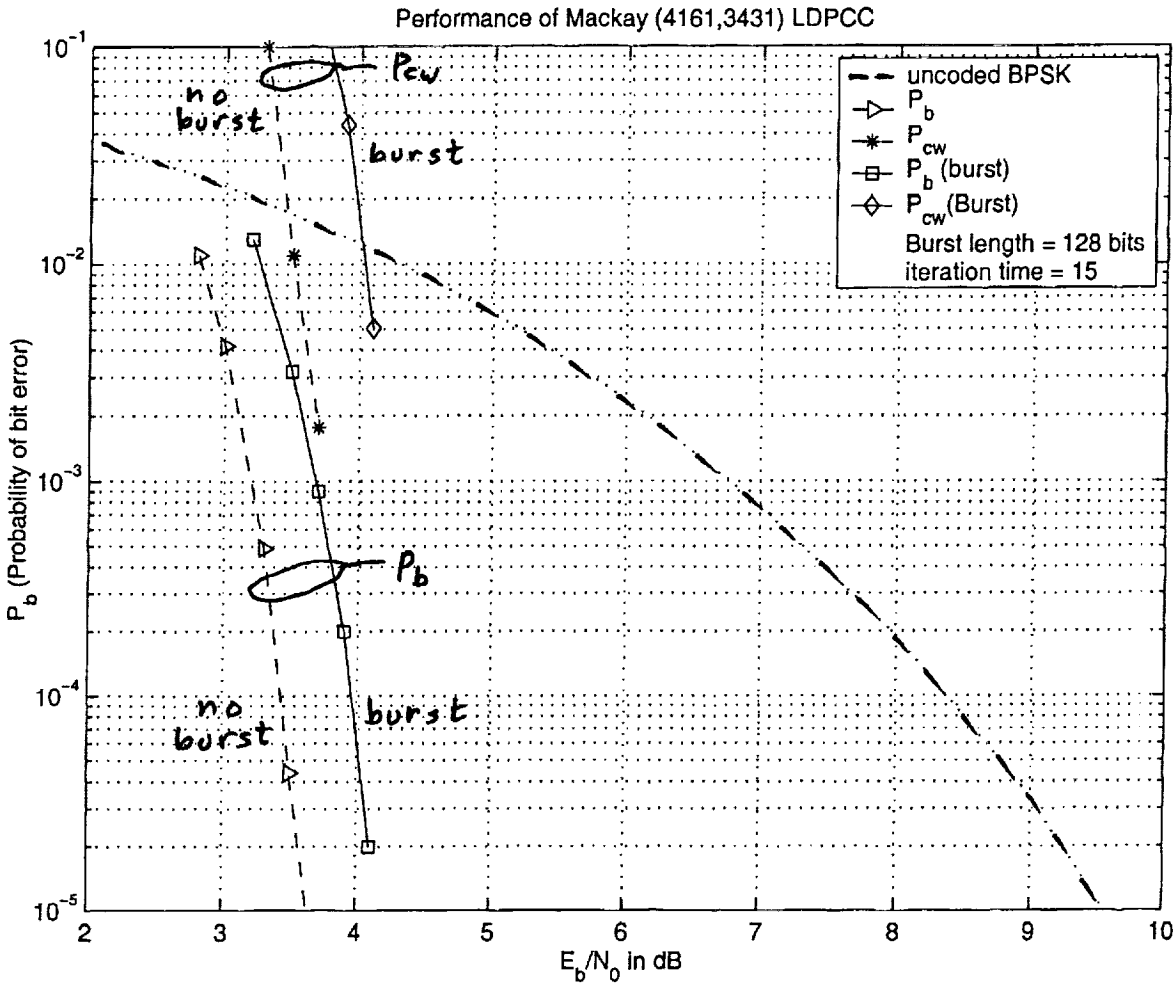
    3. the low-density property leads to very powerful codes with decoders lower in complexity than turbo decoders

- the initial designs on LDPC codes (Gallager and MacKay) involved random designs with certain row and column constraints (e.g, # 1's per column $k_c > 2$ and the # 1's per row $k_r > k_c$)

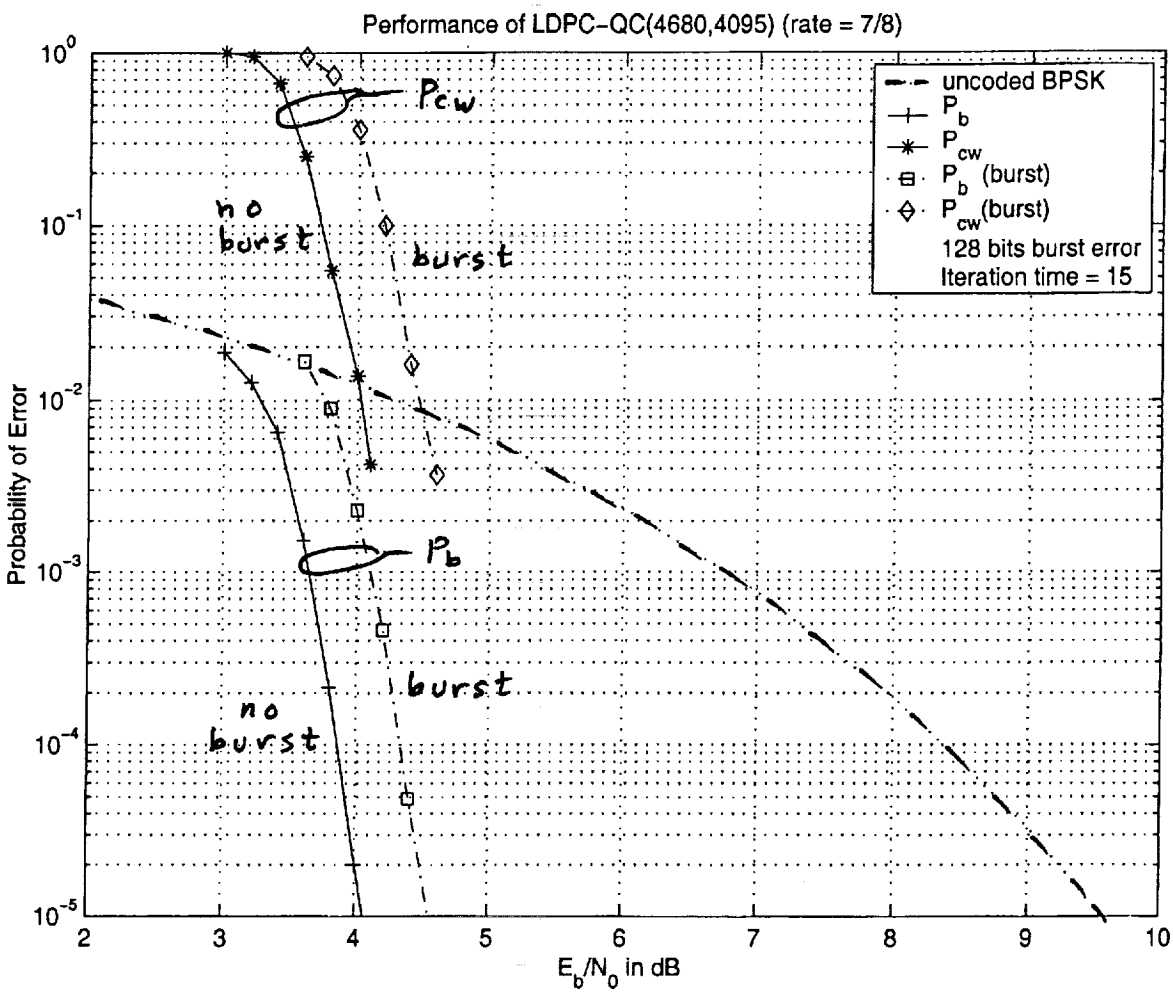
- the problem with randomly generated codes is that the *encoder* is now complex: $\mathbf{c} = \mathbf{uG} = \mathbf{u}\,[\,\mathbf{I} \mid \mathbf{P}]$ (imagine if **G** was 9000 x 10000 so that P was 9000 x 1000)

- more recently, Shu Lin and others have been looking at algebraic and combinatoric designs

- we have been examining both approaches for CCSDS near-earth standards work



A rate $r = 0.82$ MacKay LDPC code with BPSK/QPSK signaling on an AWGN channel, with and without RFI bursts.



A rate $r = 7/8$ (= 0.875) quasi-cyclic LDPC code based on difference sets for BPSK/QPSK signaling on an AWGN channel, with and without RFI bursts.

RAM Search Viterbi Detector Performance Over Nonlinear Channels

Alejandro Lima Pérez

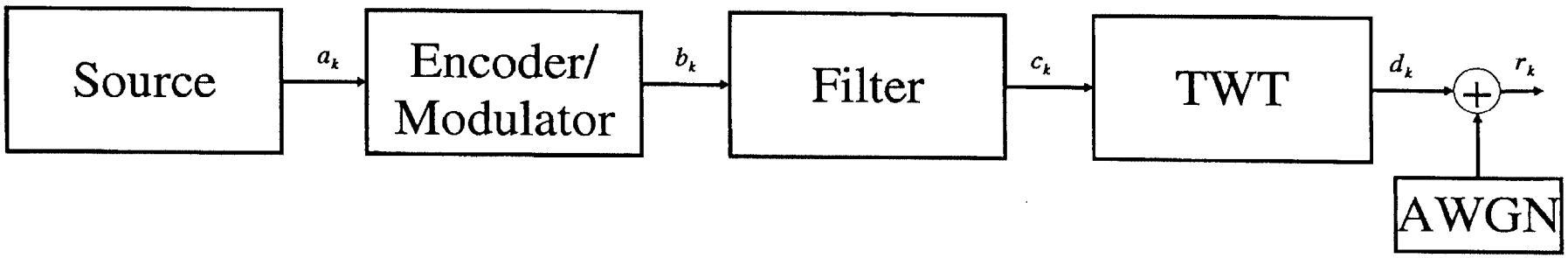
William E. Ryan

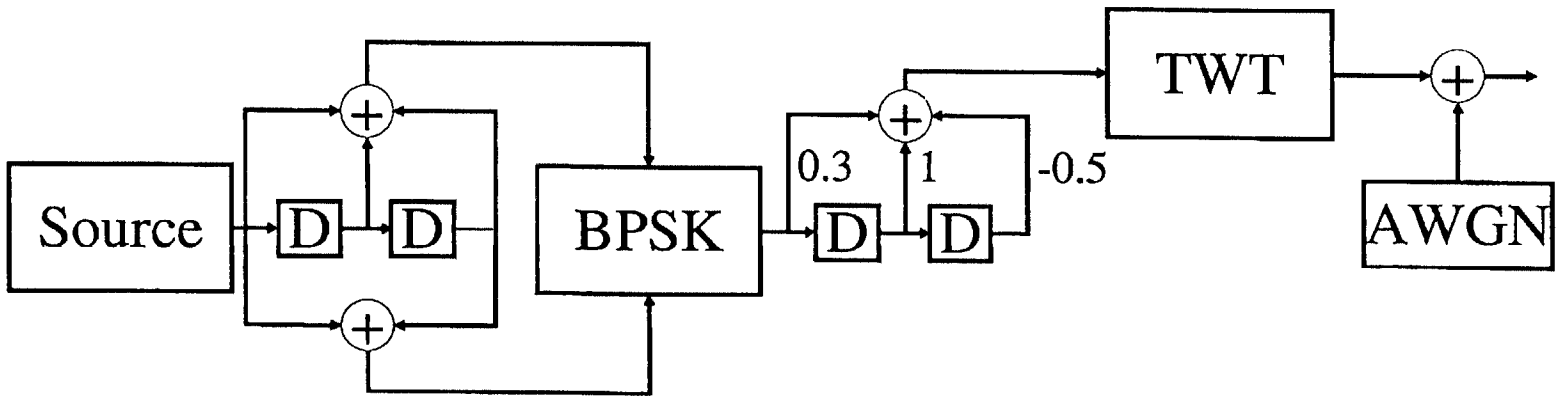
March. 5, 2001

University of Arizona

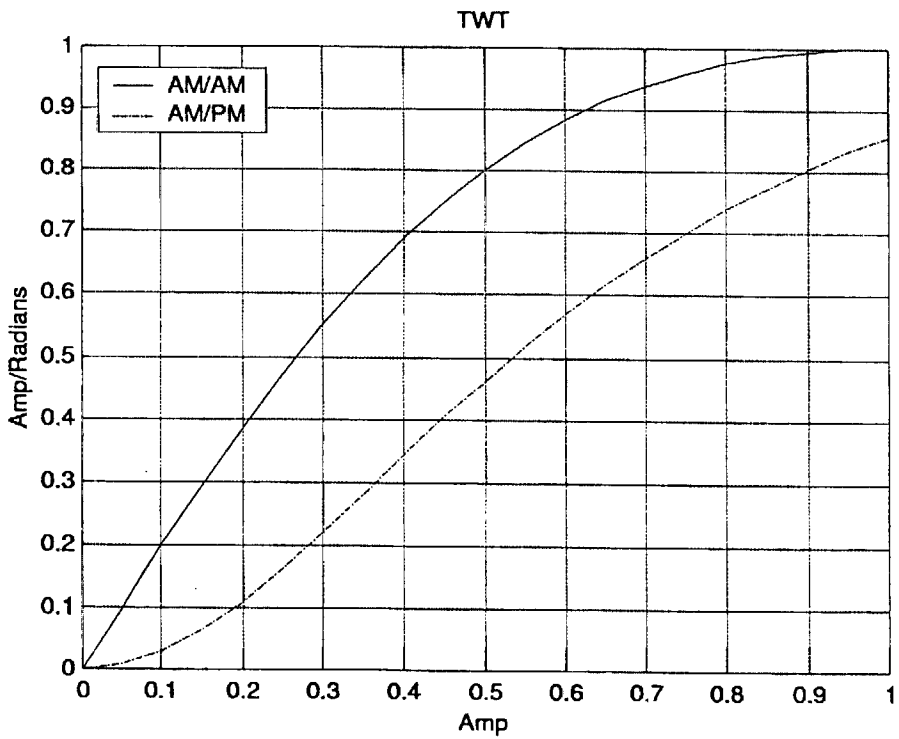
Department of Electrical and Computer Engineering

Communication Channel

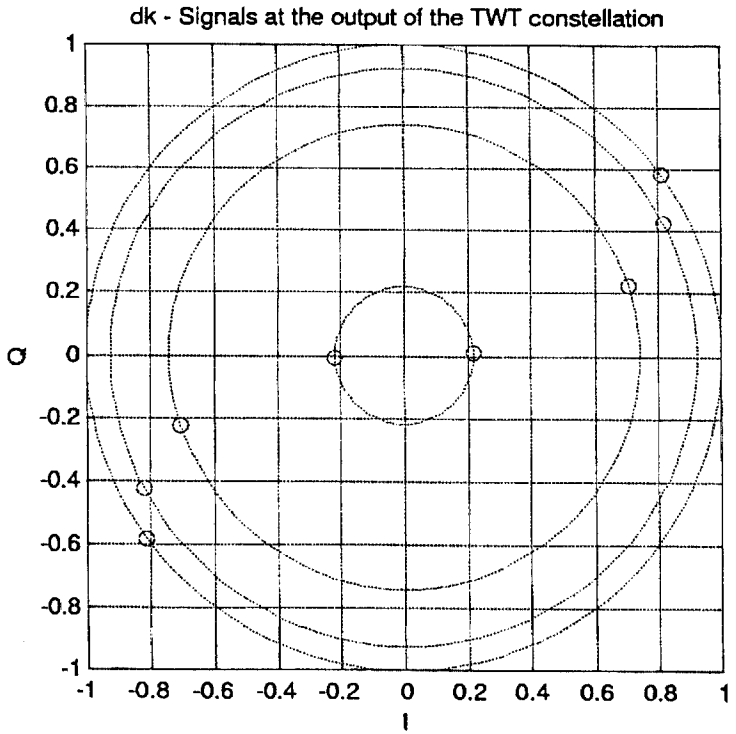




Amplifier

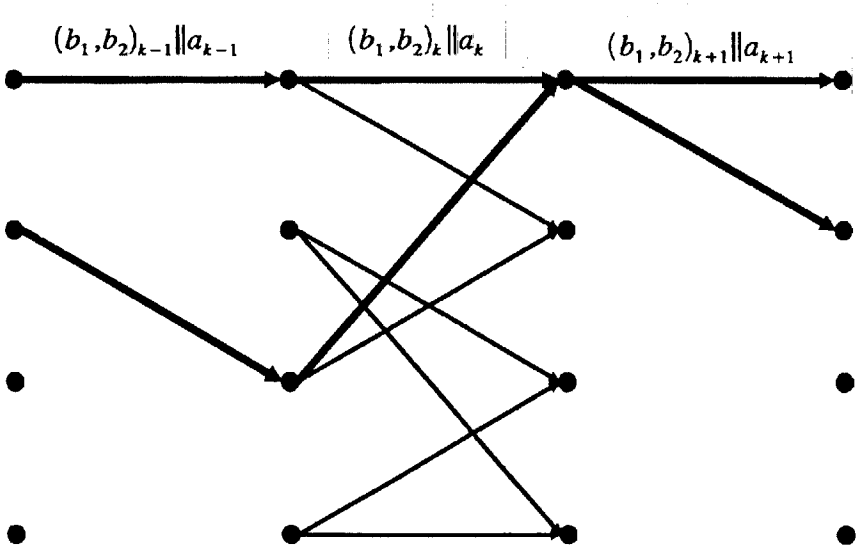


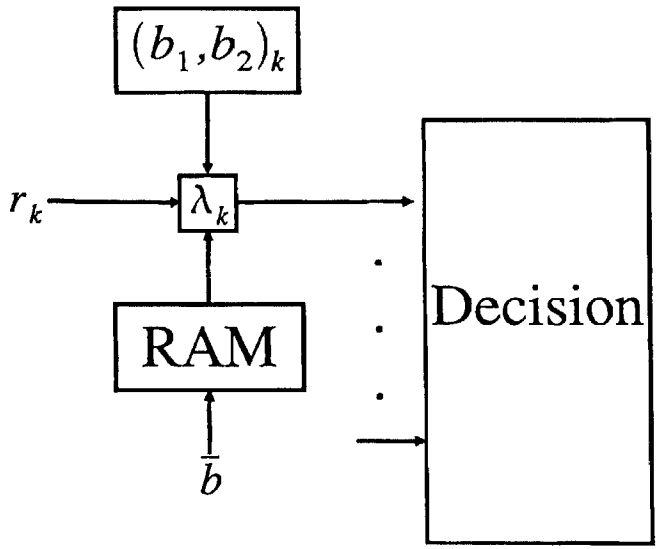
Constellation



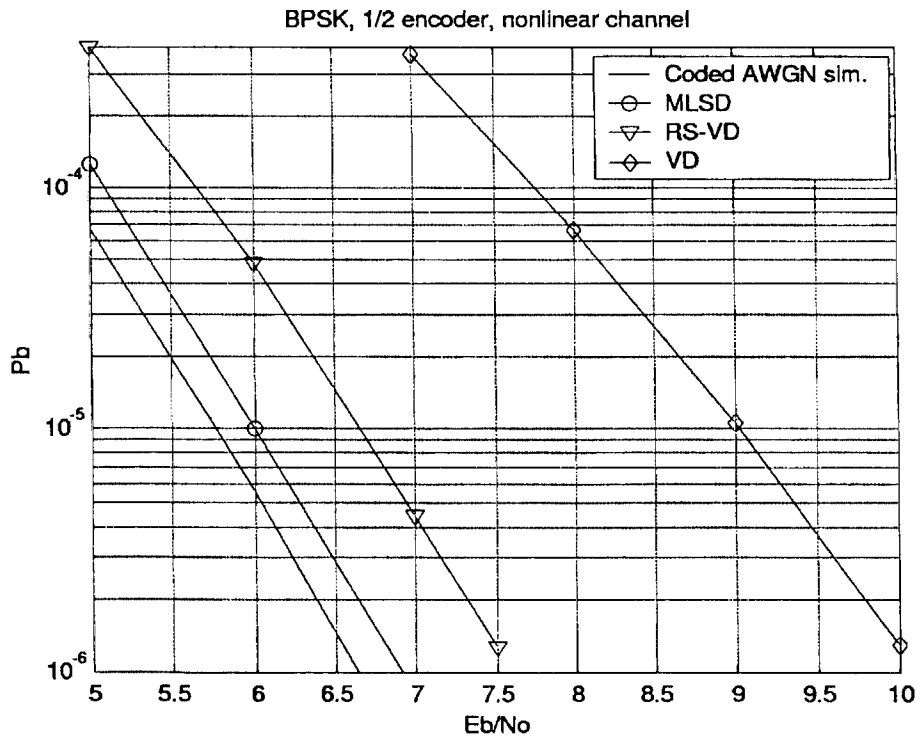
Receiver

$$\lambda_k=[r_{1k}-b_{1k}-RAM\,(b_{2,k-1},b_{1k},b_{2k})]^2+[r_{2k}-b_{2k}-RAM\,(b_{1k},b_{2k},b_{1,k+1})]^2$$

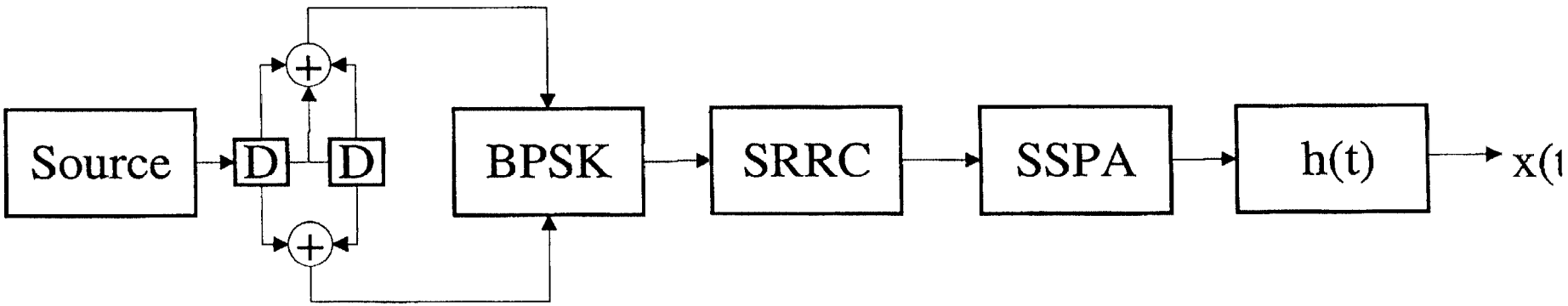


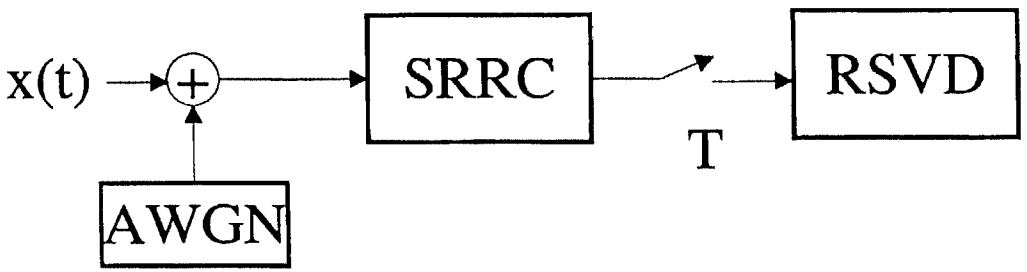


RS-VD Performance

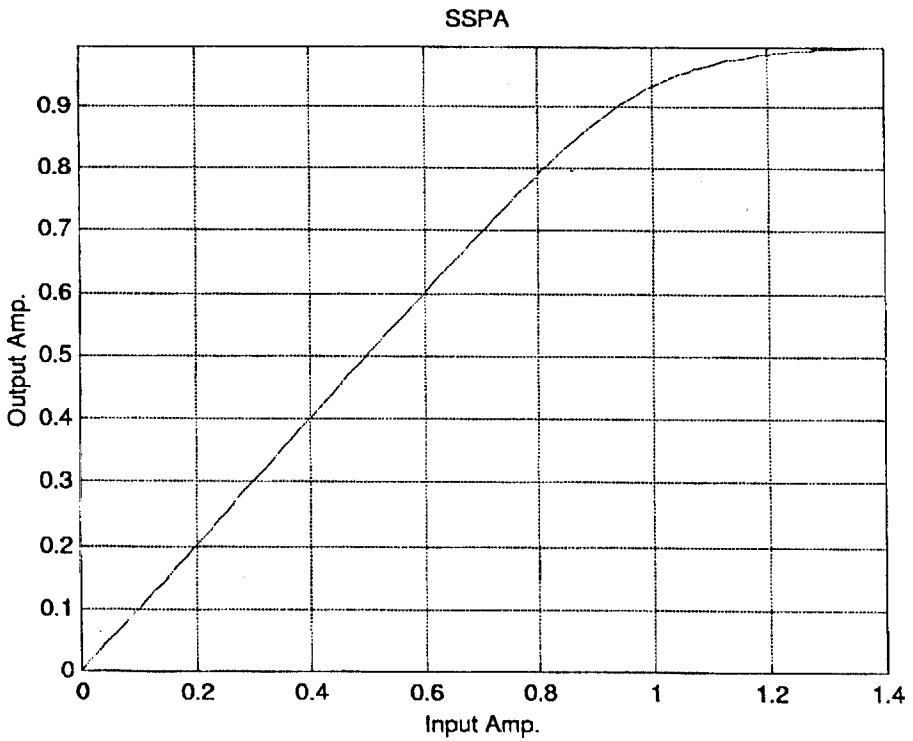


Wireless Channel

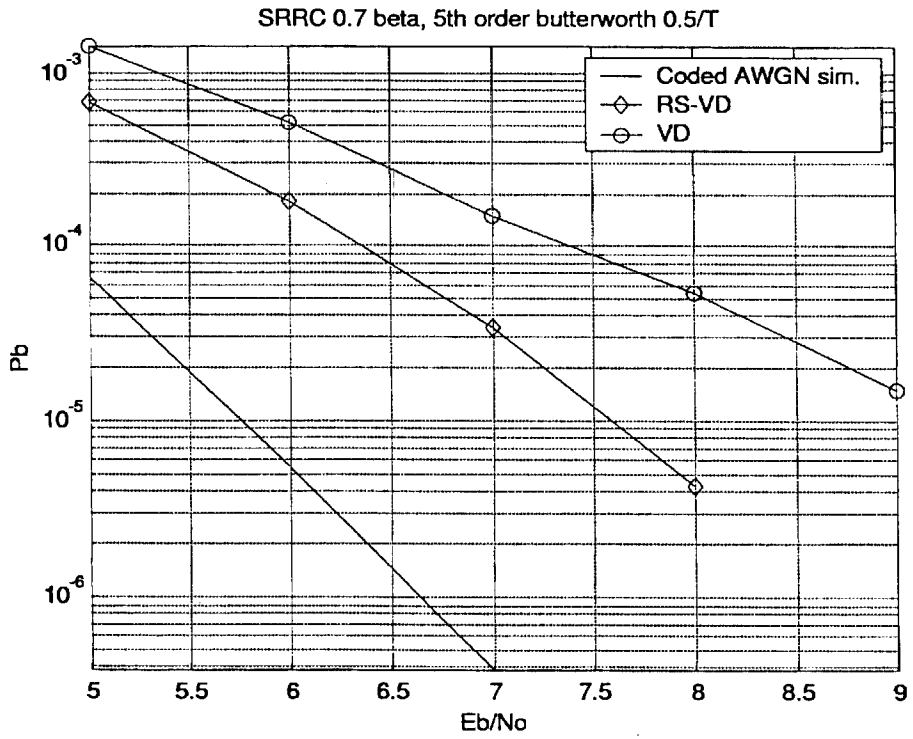




Solid State Power Amplifier



RS-VD Performance



Scalable Motion Compensated Video Compression with Reduced-Complexity Encoding for Remote Transmission

Prof. Charles Creusere

Klipsch School of Electrical & Computer Engineering

New Mexico State University

Topics

- Introduction
- Background
  - Conventional DPCM-Transform Method
  - Subband Methods
- Out-of-Loop Compensation
- Results
- Conclusions
- Future Research

Introduction

- Remote Transmission implies:
  - Limited weight and volume are available for video encoder
  - Antenna gain and transmission power are limited
  - Therefore, the communications channel has limited bandwidth and may be error prone

Introduction

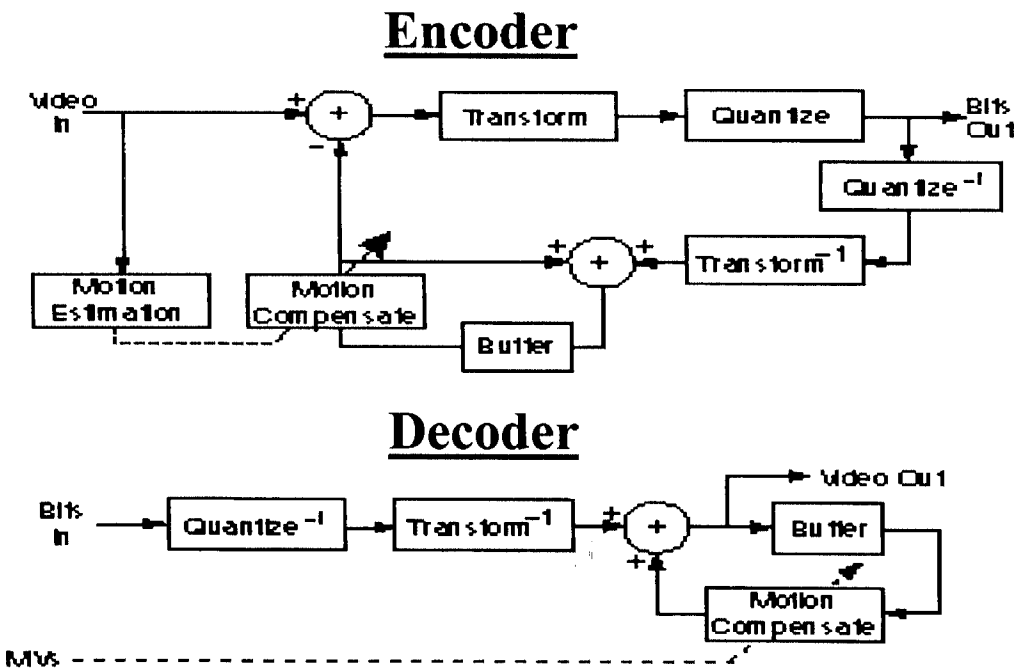
- Space and power limitations on the remote platform imply that the encoder should be low complexity
- Channel bandwidth limitation suggest that the encoder should be highly efficient
  - i.e, it must be very sophisticated and thus probably highly complex

Introduction

- To achieve maximum performance on video, one must use both transformations and motion compensation
- Existing standardized encoders such as MPEG 1 & 2 and H.263+ are not well suited to remote transmission
  - The motion compensation process makes the complexity of their encoders considerably higher than that of their decoders

Background

- Hybrid DPCM-transform video compression:

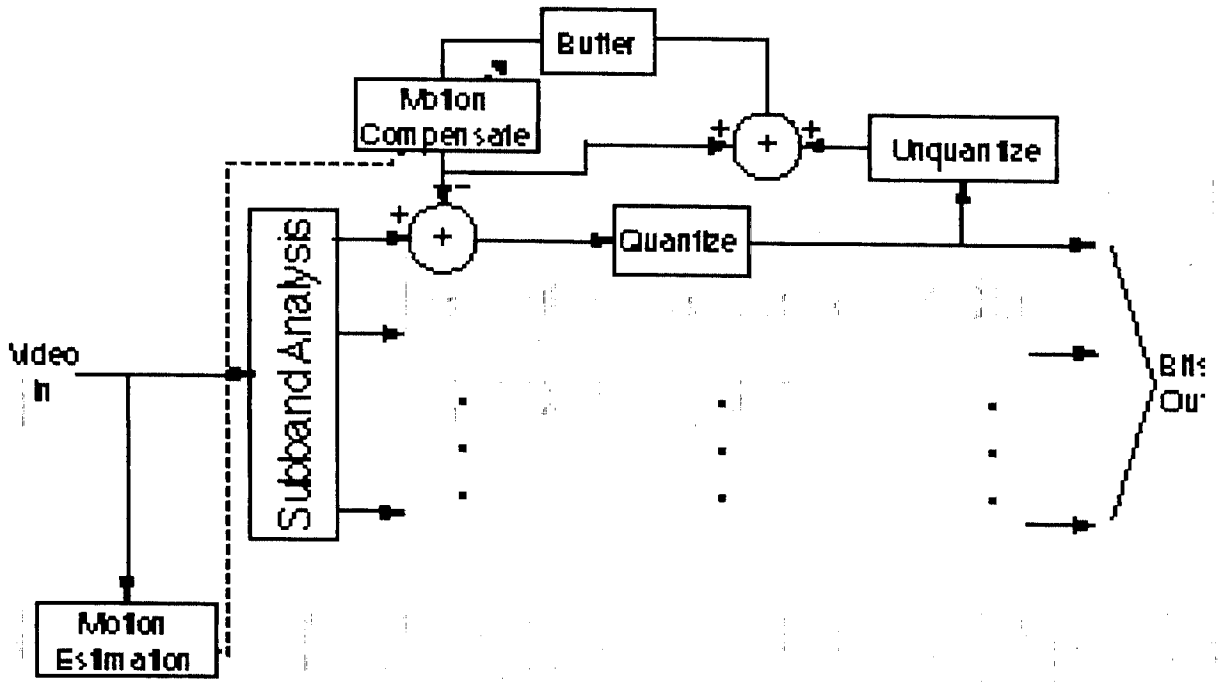


Hybrid DPCM-Transform Methods

- Encoder Complexity Issues:
  - Encoder contains the complete decoder
  - Transform complexity is double that of the decoder
  - Motion estimation must be performed by encoder

In-Subband Motion Compensation

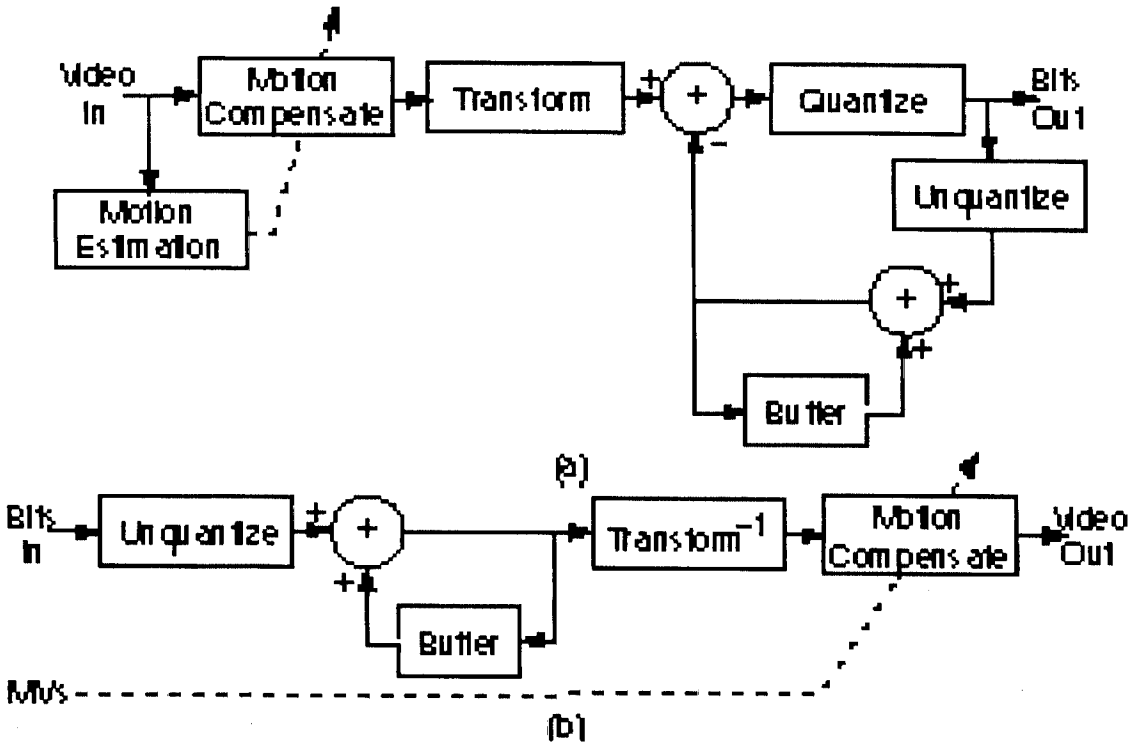
Encoder



In-Subband Motion Compensation

- Advantage:
  - No inverse transform is required in encoder => reduced complexity
- Disadvantage:
  - Motion compensation does not work well in subbands because filter bank/transform is decimated => shift varying

Out-of-Loop Motion Compensation



(a) is encoder; (b) is decoder

Out-of-Loop Motion Compensation

- Salient Features:
  - Motion compensation is performed in spatial domain
    - Eliminates problems associated with shift-varying transforms
  - Differencing is performed in the transform domain
    - Eliminates need for expensive inverse transform in the encoder
  - Supports resolution scalability with appropriate transform (e.g., wavelet) coefficient encoding
    - Heterogeneous communications networks
    - Channels with time-varying capacity

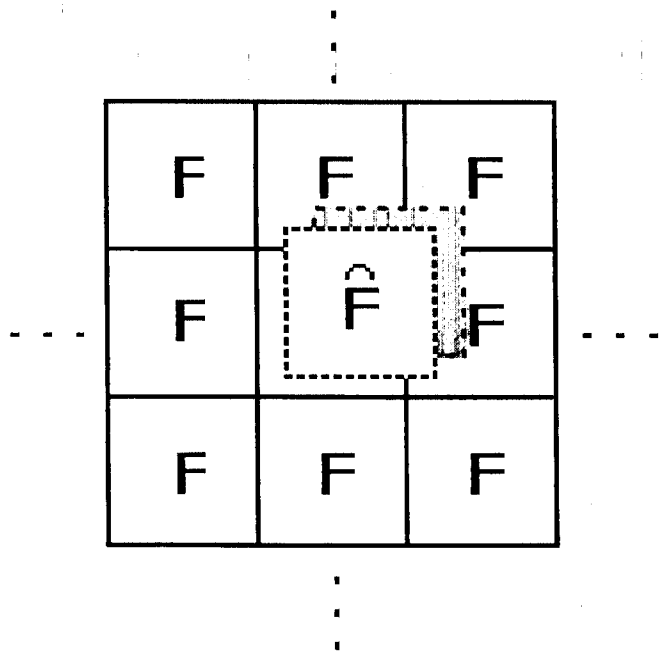
Out-of-Loop Motion Compensation

- **Limitation**: Motion compensation algorithm *must* be invertible
  - This is not required for conventional DPCM-transform encoding
- Simplest invertible method: periodic pan compensation (PPC):

$$\mathrm{PPC}\{F(x,y)\} = F((x-\Delta m)\bmod(X),(y-\Delta n)\bmod(Y))$$

Out-of-Loop Motion Compensation

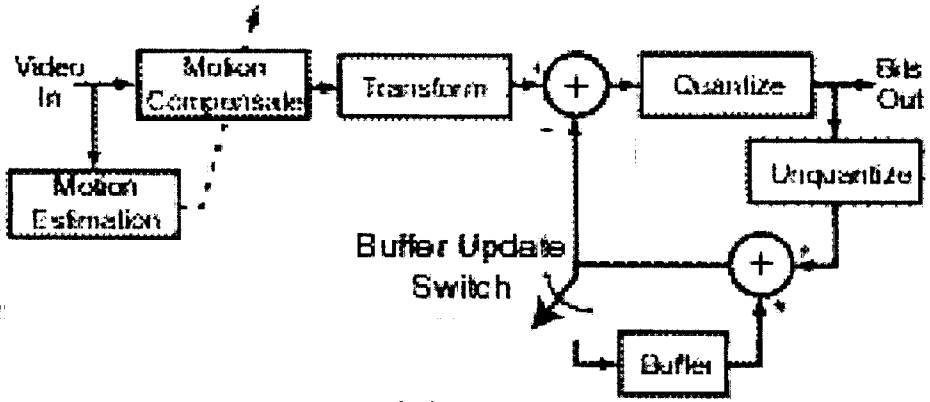
- PPC can be viewed as a window into an infinitely periodic image plane:



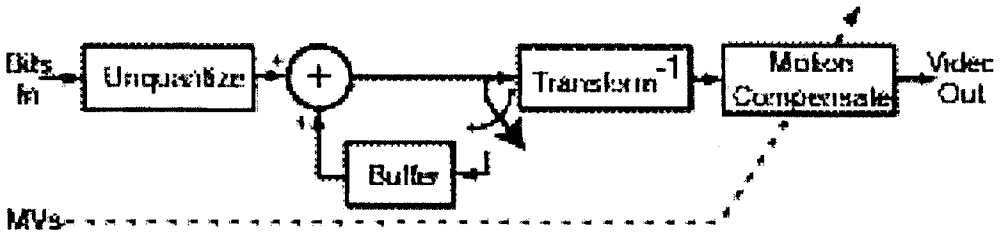
Out-of-Loop Motion Compensation

- To handle more complex motion:
  - PPC can be applied in blocks
  - PPC can be generalized to handle skewing motion: G-PPC (allows for rotational compensation)
  - PPC and G-PPC can be designed to compensate for subpixel motion

Frame-Rate Scalable Motion Compensation



(a)



(b)

(a) is encoder; (b) is decoder

Frame-Rate Scalable Motion Compensation

- Buffer Update Switch:
  - Always closed => single frame rate
  - Alternately open/close => 2 frame rates
    - Full and half
  - Closes every 4th frame => 4 frame rates
    - Full, ¾, ½, and ¼
- Wavelet transform and resolution-embedded encoding provides resolution scalability within this framework

Results

- Averaging over 5 video sequences
  - 50 to 500 frames
  - Sizes from 176x144 (QCIF) to 352x288 (CIF)
  - Bit Rates: 0.05 to 3.5 bits/pixel (bpp)
- Average result:
  - Encoder speed: 33% faster
  - Bit rate: 9.2 % lower
  - Mean Squared Error (MSE) in reconstruction: 29.6% lower

Results

Original

Frame Differencing

0.39 bpp, MSE= 382

Results

Conventional Pan Compensation

0.38 bpp, MSE= 494

OOL Pan Compensation

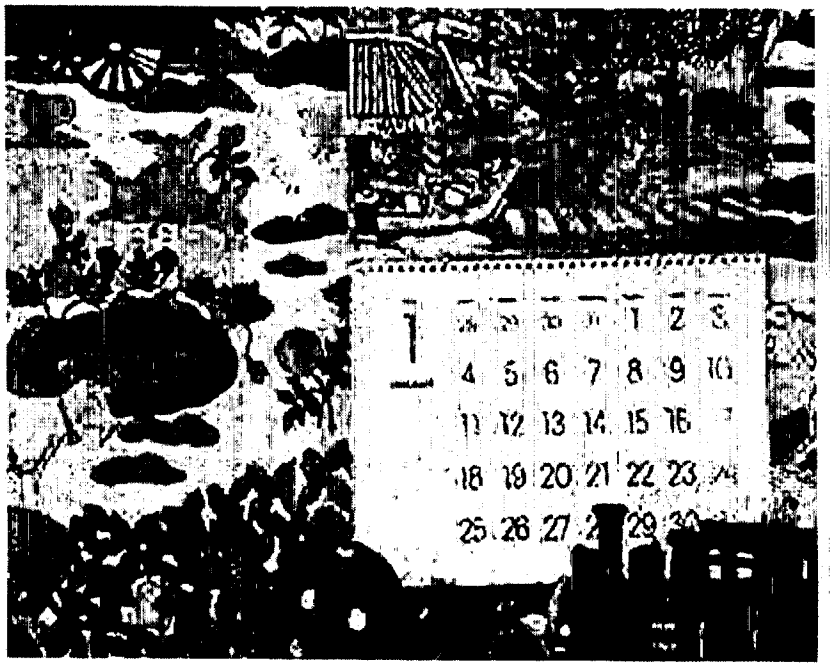
0.32 bpp, MSE= 383

Results

OOL: 4 Blocks

0.29 bpp, MSE= 386

OOL: 16 Blocks



0.33 bpp, MSE= 409

Results: Scalability

Scalable video decoding of *amb.256* sequence using OOL-Pan compensation. The average bit rate of the encoded sequence is 0.955, the average MSE is 2.42, and the residual update rate is 4

Frame Rate	Resolution	Avg. Bit Rate	Avg. MSE	Decoding Time
Full	Full	0.955	2.42	48.64
Full	1/4	0.462	2.34	14.16
Full	1/16	0.164	0.308	5.05
1/2	Full	0.513	2.39	24.77
1/4	Full	0.289	2.38	12.72
1/2	1/4	0.250	2.24	7.47
1/2	1/16	0.089	0.250	2.82
1/4	1/4	0.142	2.359	3.92
1/4	1/16	0.050	0.243	1.55

Conclusion

- OOL Compensation provides the expected benefit of reducing encoder complexity: 33% on average
- In addition, it also supports the creation of both rate and resolution scalable bit streams
- An unexpected benefit: it achieves better rate-distortion performance than conventional DPCM-transform pan compensation when used with the same transform and encoder.

Future Research

- Adding robustness to the bit stream
  - 'Leaky' prediction
  - Coefficient Partitioning
- Developing new invertible motion compensation operators

Parallel Digital Architectures for Direct Sequence Spread Spectrum Receivers

---

Stephan Berner and Phillip De Leon

New Mexico State University

Center for Space Telemetering and Telecommunications

Las Cruces, NM 88003

Outline

- Why?
- Part I: Review of Parallel QAM Receivers
  - (JPL/GSFC 1995, 1998)
- Part II: Proposed Parallel Adaptive DSSS Receiver
- Part III: Analysis of Proposed Parallel Receiver
- Conclusions

Receivers: Why Implement Digitally?

- It is highly desirable to implement as many receiver functions digitally
  - Possible reduction in size and power consumption
  - Potential for single IC solution and better reliability
  - Adaptable, e.g. analog equalizers difficult; reconfigurable
  - Potential to replace costlier analog components with cheaper digital equivalents
  - Possibly better performance

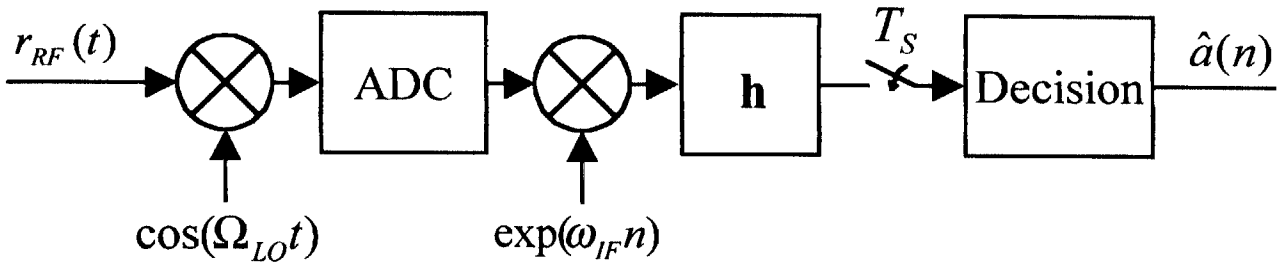
Receivers: Why Parallelize?

- With digital implementations of serial receivers, we can only handle sample rates up to clock frequency of hardware
- One approach to overcome this limitation is to parallelize the receiver, i.e. decompose the high rate input signal into many, parallel lower rate signals which can be handled digitally

Part I: Review of Parallel QAM Receivers (JPL 1995)

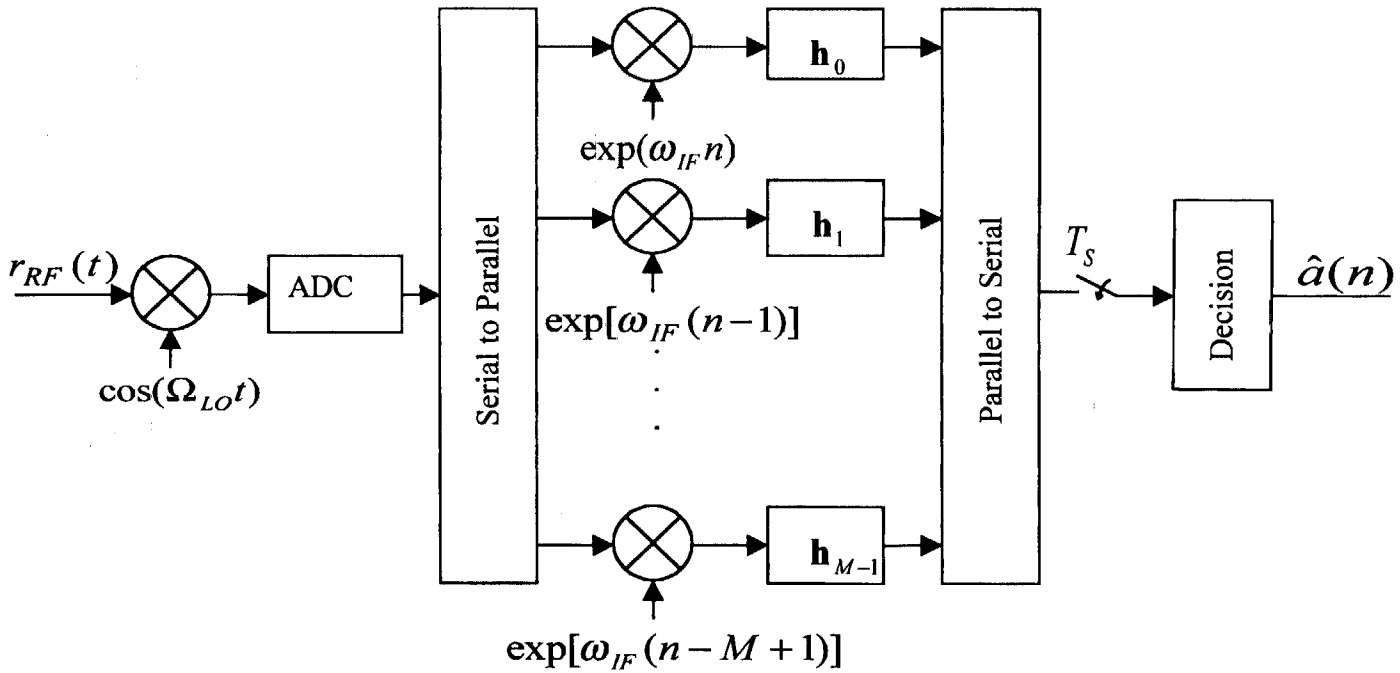
Serial Implementation of QAM Receiver

- Intermediate Frequency (IF) signal is digitized
- Translation from IF to baseband, matched filtering, symbol rate sampling, and symbol decision are all performed digitally



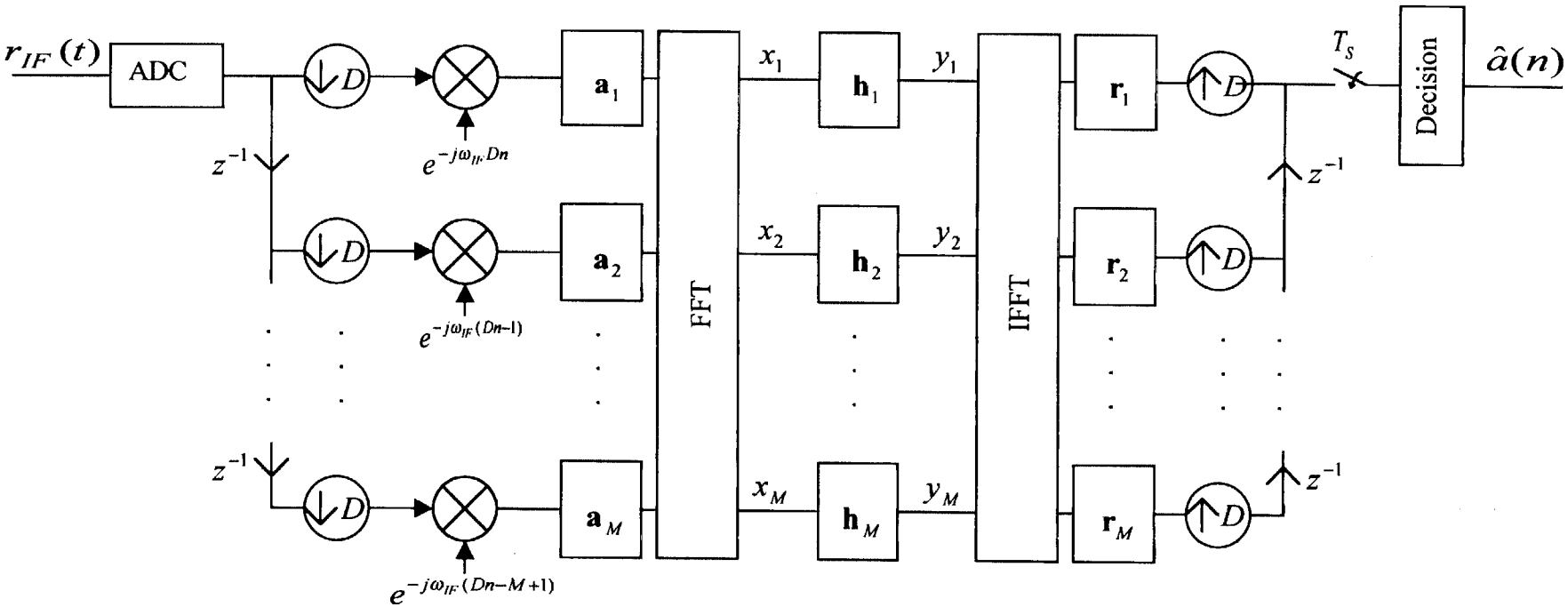
Parallel Implementation of QAM Receiver

- High rate input signal is divided into parallel, lower rate signals. Several implementation possibilities for serial-to-parallel converter



Possibility #1: Parallel QAM Receiver Based on Filterbanks (JPL, 1995)

- Serial-to-parallel conversion by analysis filterbank (implemented in polyphase form)

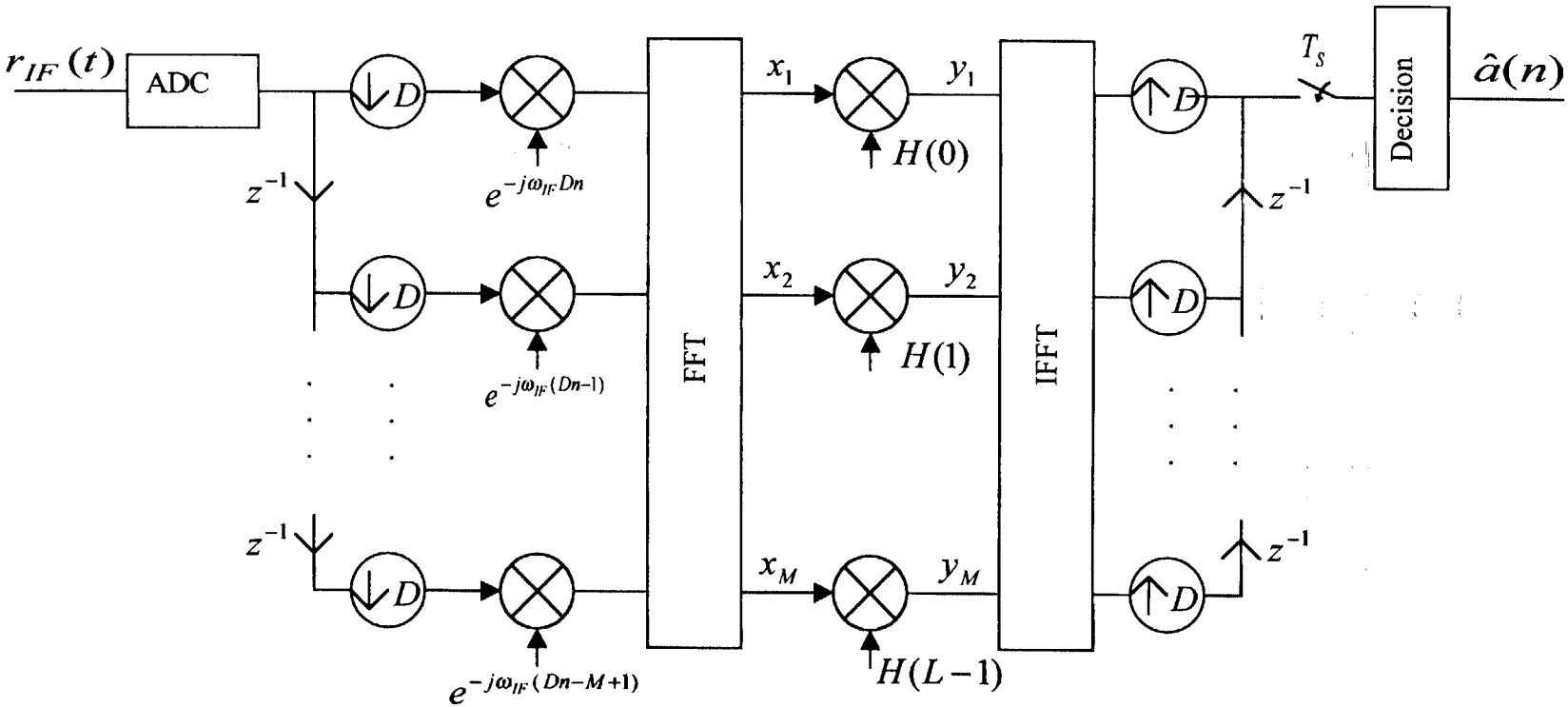


Possibility #1: Parallel QAM Receiver Based on Filterbanks (cont.)

- Delay line runs at high rate, everything else at lower rate
  - IF to baseband translation, matched filtering performed digitally
- In filterbank implementation, require high order filters and careful design near crossover frequencies
- As will be shown, performance (BER) degrades with increasing number of subbands (not well scalable)

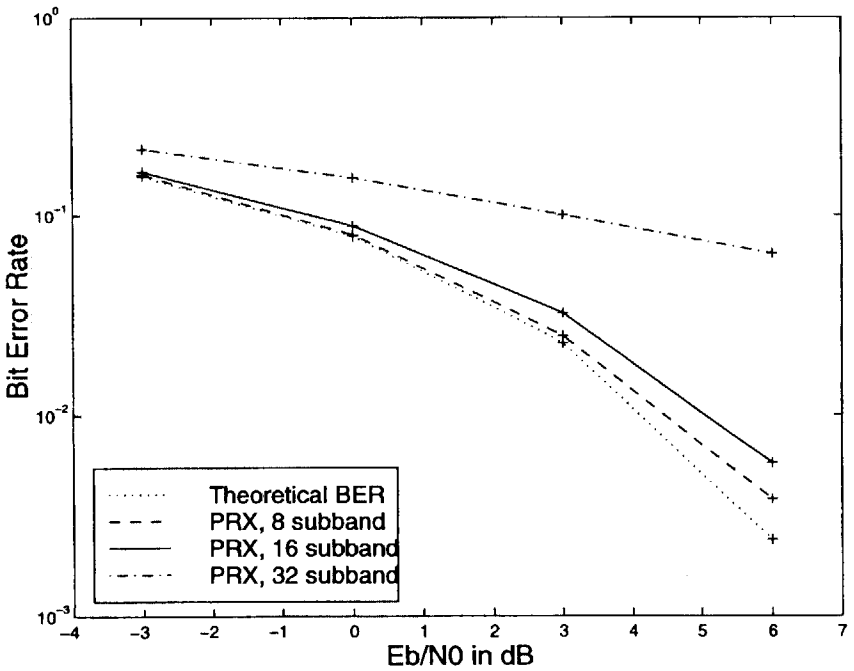
Possibility #2: Parallel QAM Receiver Based on Frequency Domain Filtering (GSFC, 1998)

- Matched filtering (convolution) is performed by multiplication in the frequency domain

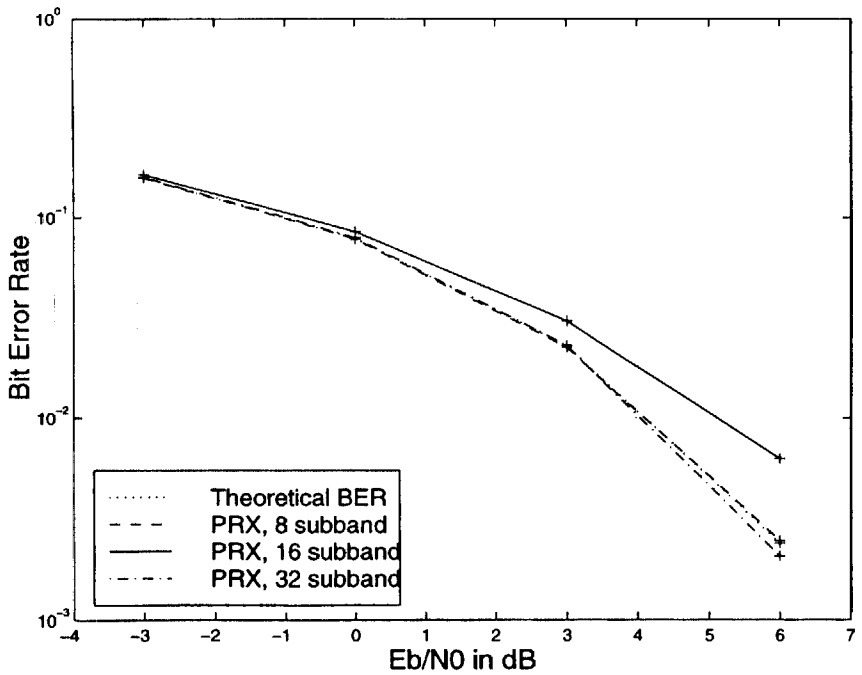


Comparison of the Two Parallel Approaches

- Simulated both receivers for AWGN



Filterbank Approach



Frequency Domain Filtering Approach

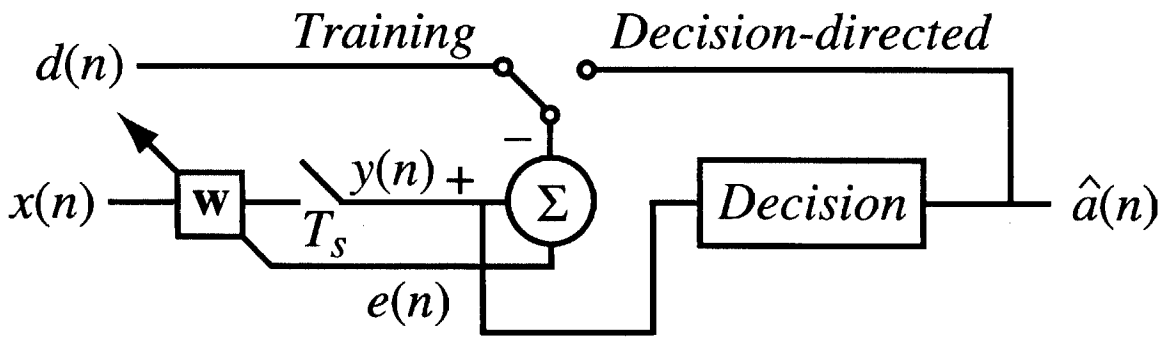
IC Implementation

- ASIC implementations of BPSK, QPSK, QAM parallel receivers have been reported (A. Gray at JPL/Caltech, P. Ghuman at NASA/GSFC)
  - Bandpass sampling of IF at 4x data rate
  - 75MHz ASIC
  - 16 parallel subbands for 300M symbols/sec data rate

Part II: Proposed Parallel Adaptive DSSS Receiver

Review of Adaptive DSSS Receivers (Fractionally Spaced)

- Features/properties
  - Adaptive filter spans at least over one symbol, contains samples of received signal
  - Filter coefficients are updated at symbol rate using LMS, NLMS, RLS adjustment algorithms
    - Convergence depends on initialization



Review of Adaptive DSSS Receivers (cont.)

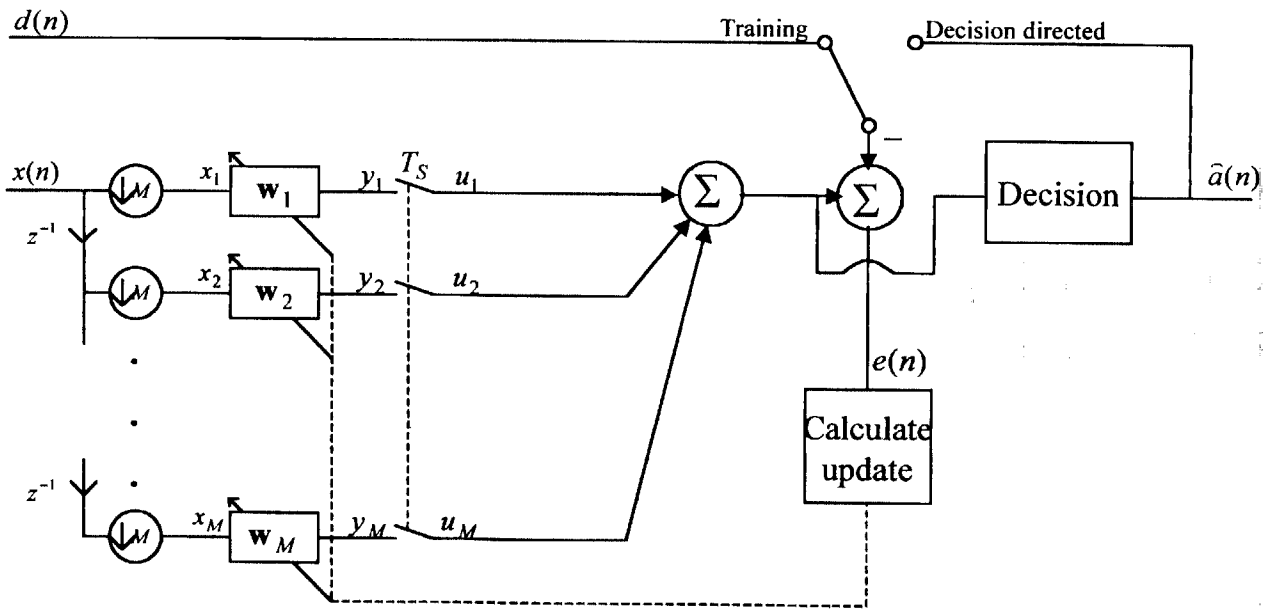
- Filter taps after training (AWGN case) are equal to pulse-shaped PN sequence (matched filter coefficients)
- Adaptive DSSS receiver can suppress interference and equalize channel; also performs code acquisition
- Operating conditions of adaptive DSSS receivers are different from typical adaptive filtering applications
  - Signals are cyclostationary, however, due to sampling at symbol rate they appear stationary for filter
  - For AWGN, correlation matrix is Hermitian (but not Toeplitz as usual)

$$\mathbf{s} = \begin{bmatrix} s_1 & s_2 & \cdots & s_N \end{bmatrix}^T$$

$$\mathbf{R} = \mathbf{s}\mathbf{s}^T + \sigma^2\mathbf{I}$$

Parallel Implementation of Adaptive DSSS Receiver: 1st Approach (trivial)

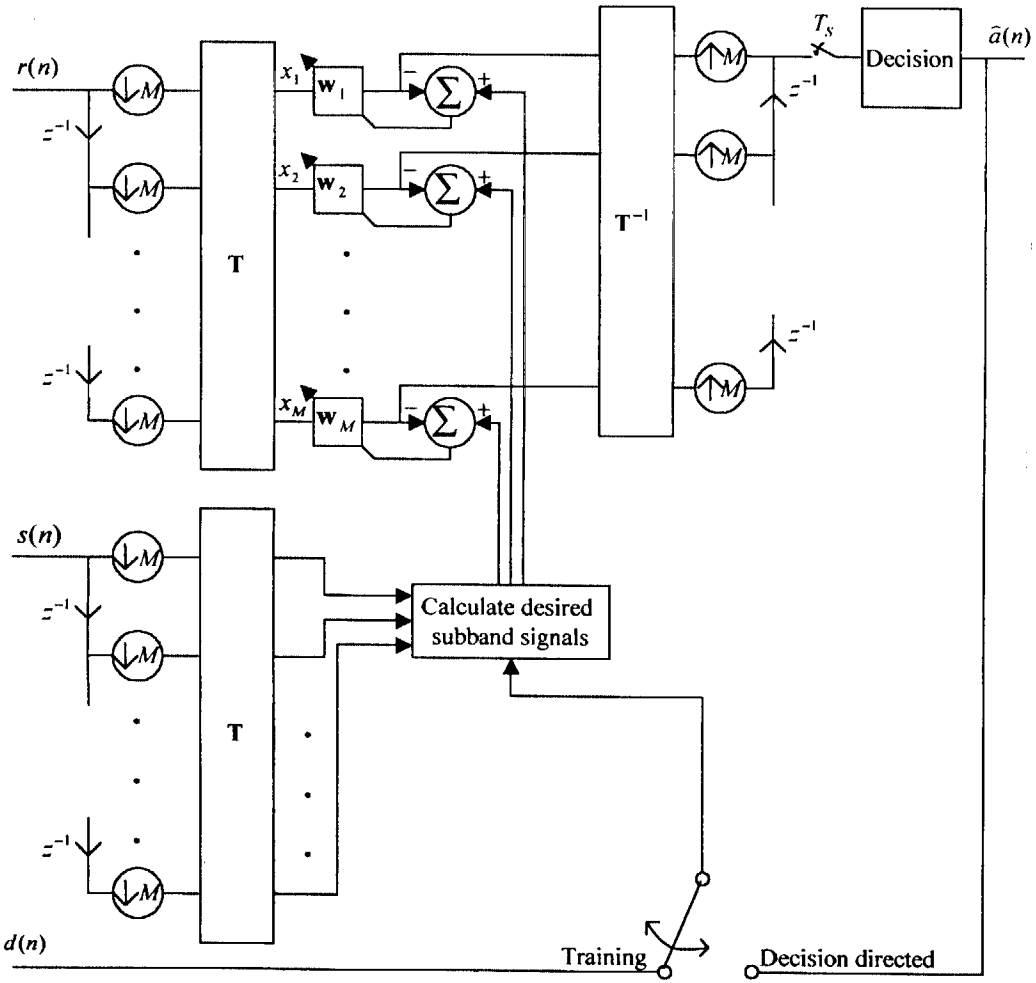
- Apply polyphase decomposition to serial adaptive DSSS receiver
  - Equivalent to serial receiver, same performance
  - Input signal decomposed into parallel lower rate signals



Parallel Implementation of Adaptive DSSS Receiver: 2nd Approach

- Apply classic subband adaptive filtering architecture
  - Filterbanks decompose input, desired signals; single adaptive filter replaced by several shorter filters
  - Used in acoustic echo cancellation (AEC) problems
- Simplify architecture, exploiting special operating conditions of adaptive receivers
  - As a first step, replace filterbanks by general transforms (matrices), $\mathbf{T}$ and $\mathbf{T}^{-1}$

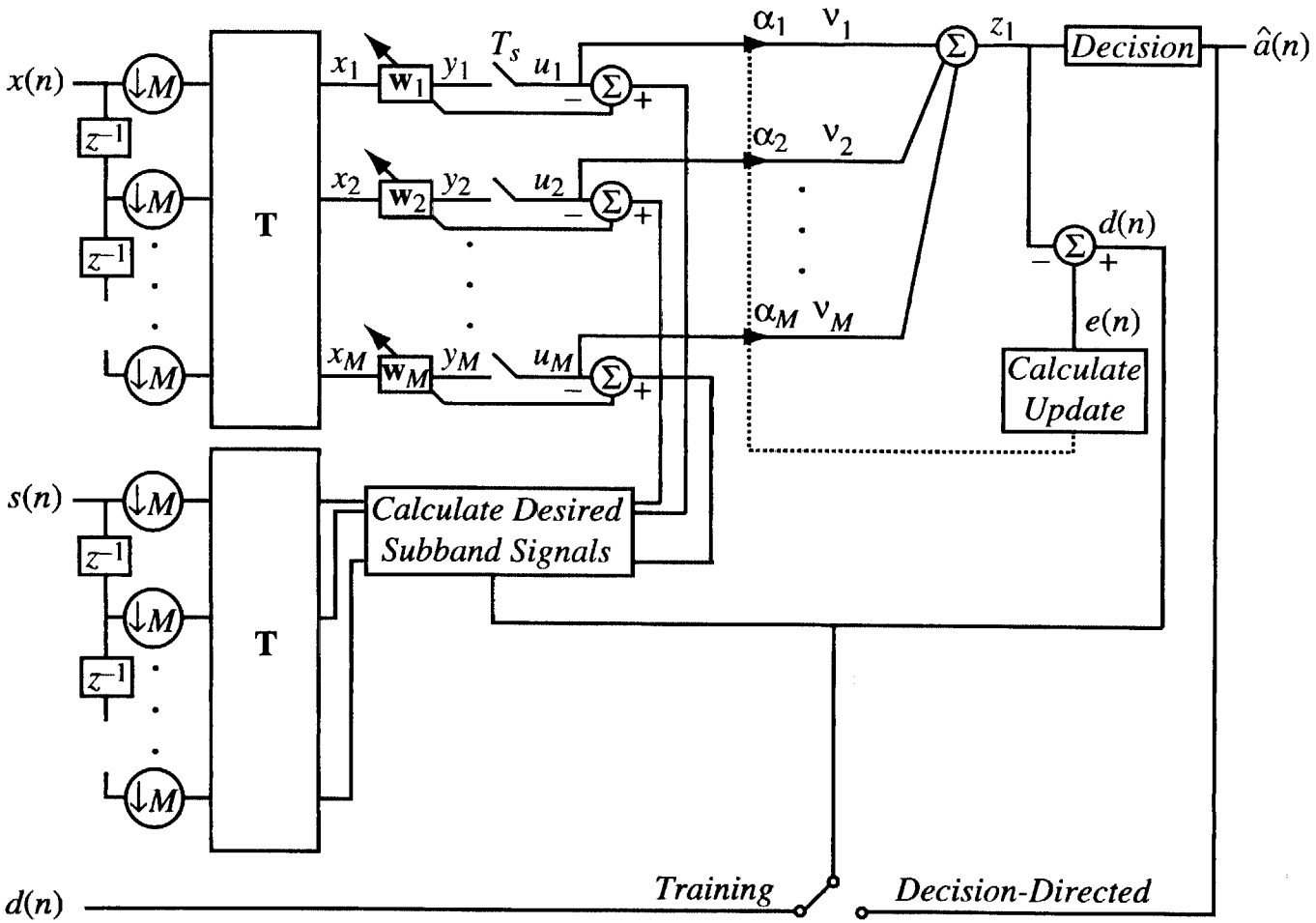
Parallel Implementation of Adaptive DSSS Receiver, 2nd Approach (cont.)



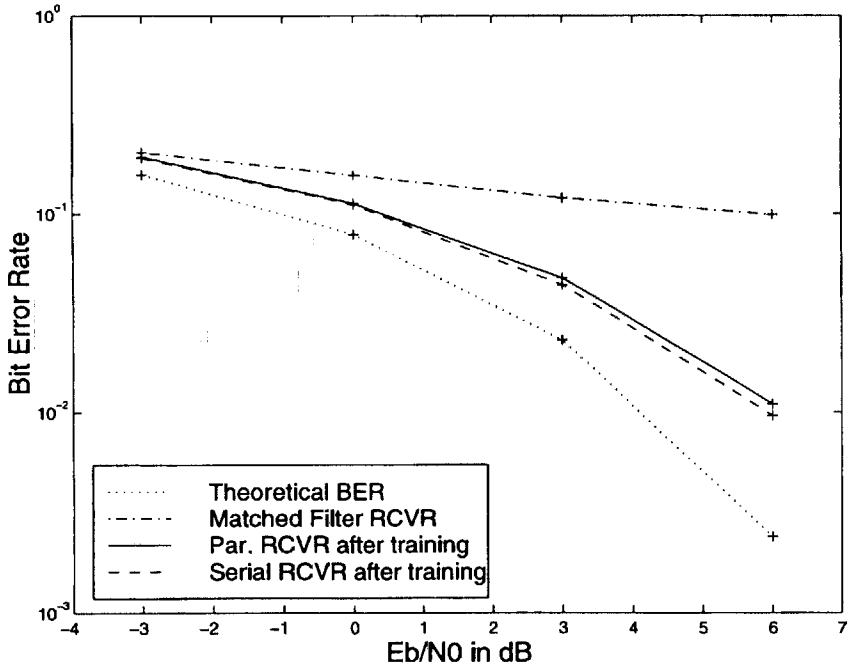
Parallel Implementation of Adaptive DSSS Receiver, 2nd Approach (cont.)

- Simplify and improve architecture
  - Assume symbol length is multiple of M
  - Inverse transform reduces to summation
  - Employ adaptive gain factors, α

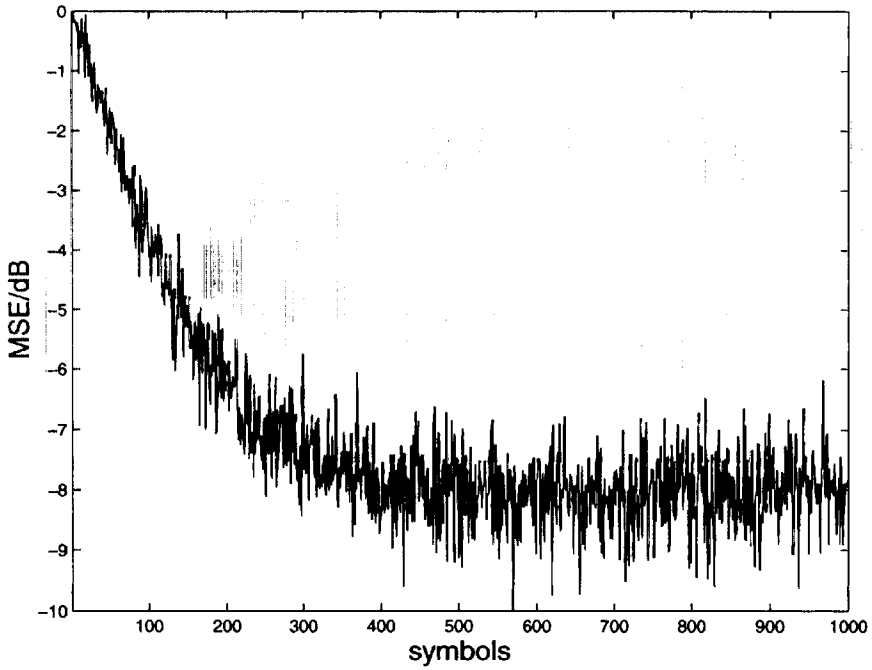
Parallel Implementation of Adaptive DSSS Receiver, 2nd Approach (cont.)



Comparison of Serial and Parallel Receiver by Simulation using NLMS

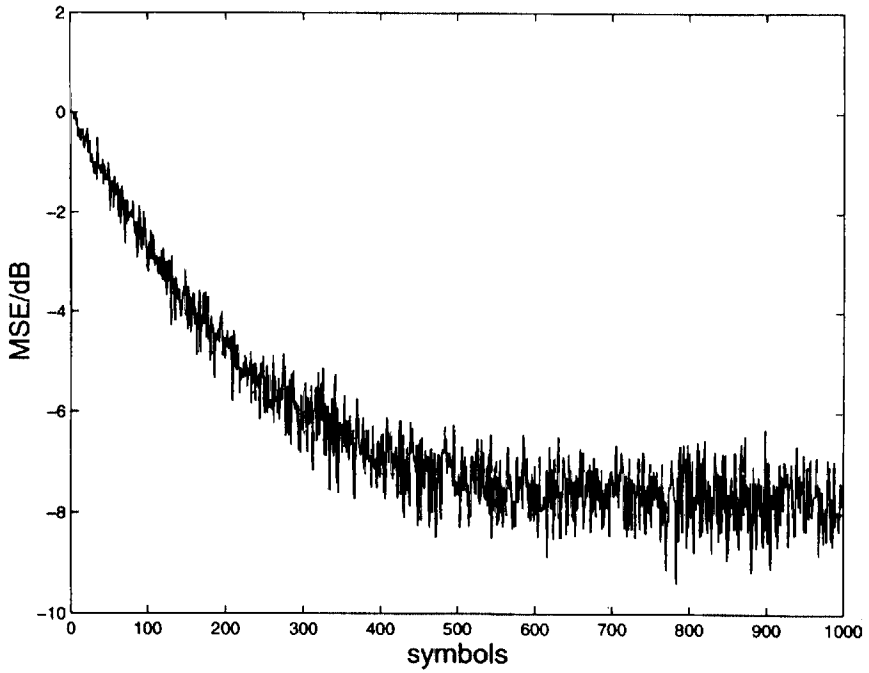


BER

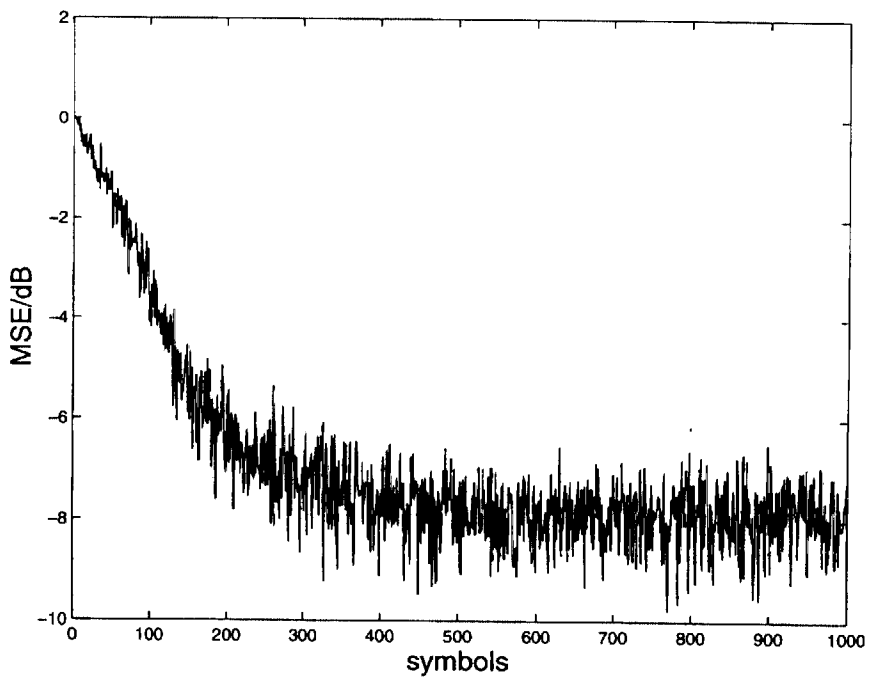


MSE of Serial Receiver

Comparison of Serial and Parallel Receiver by Simulation using NLMS (cont.)



MSE of Parallel Receiver without Adaptive Gain Factors

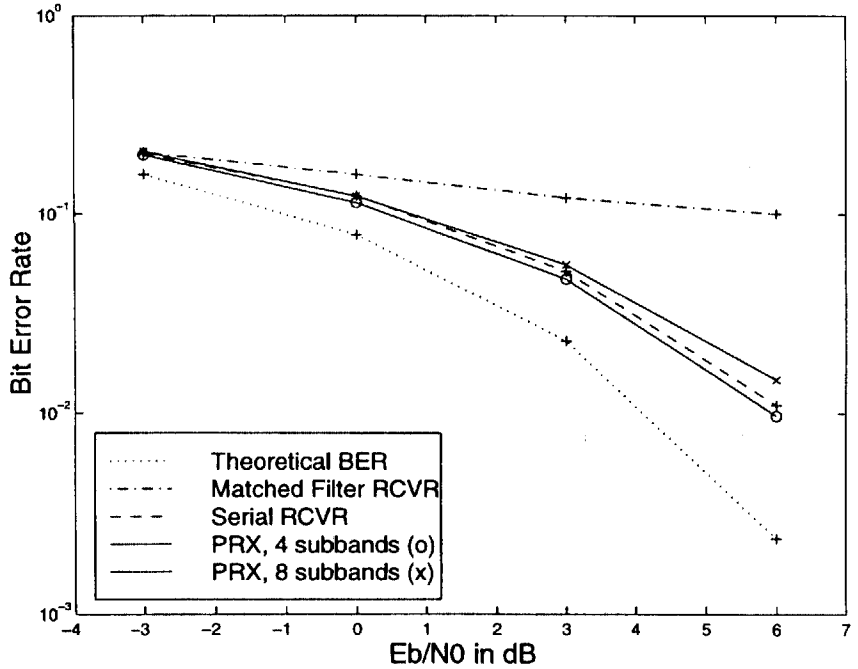


MSE of Parallel Receiver with Adaptive Gain Factors

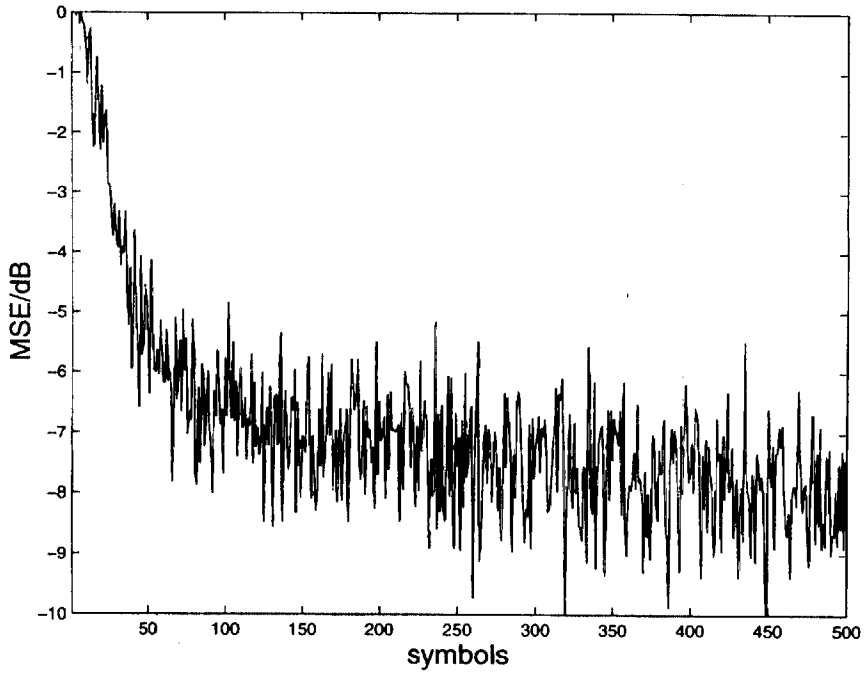
Remarks to NLMS Simulation

- Convergence rate comparison is based on same BER for serial and parallel receivers (can be achieved by step size variation)
- Simulation parameters
  - Interference by 4 other users and 3 sinusoids, each 6 dB stronger than desired signal
  - Training at 6 dB SNR
  - Length 31 PN sequence used, 4 samples per chip, SRRC pulse, 50% excess bandwidth
  - Parallel receiver has 4 "subbands" and length 32 subband filters
- Observations
  - Gain factors speed up filter convergence
  - DCT, Hadamard transforms perform well, DFT poor

Comparison of Serial and Parallel Receiver by Simulation using RLS

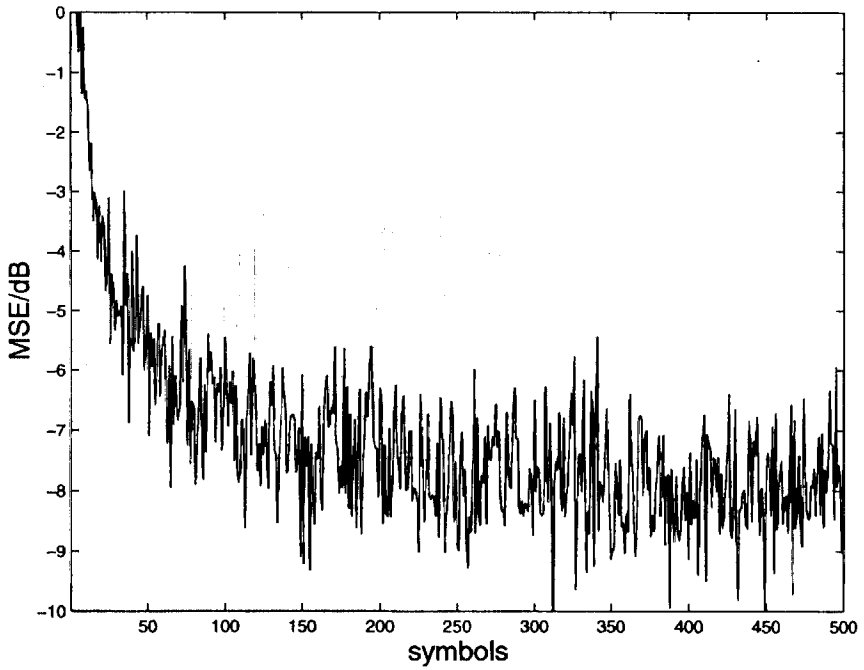


BER

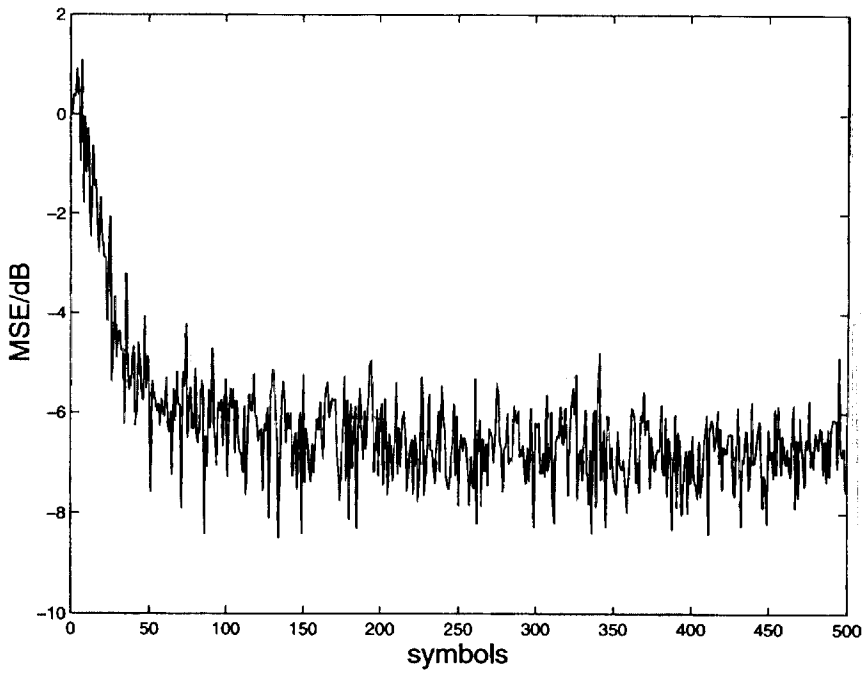


MSE of Serial Receiver

Comparison of Serial and Parallel Receiver by Simulation using RLS (cont.)

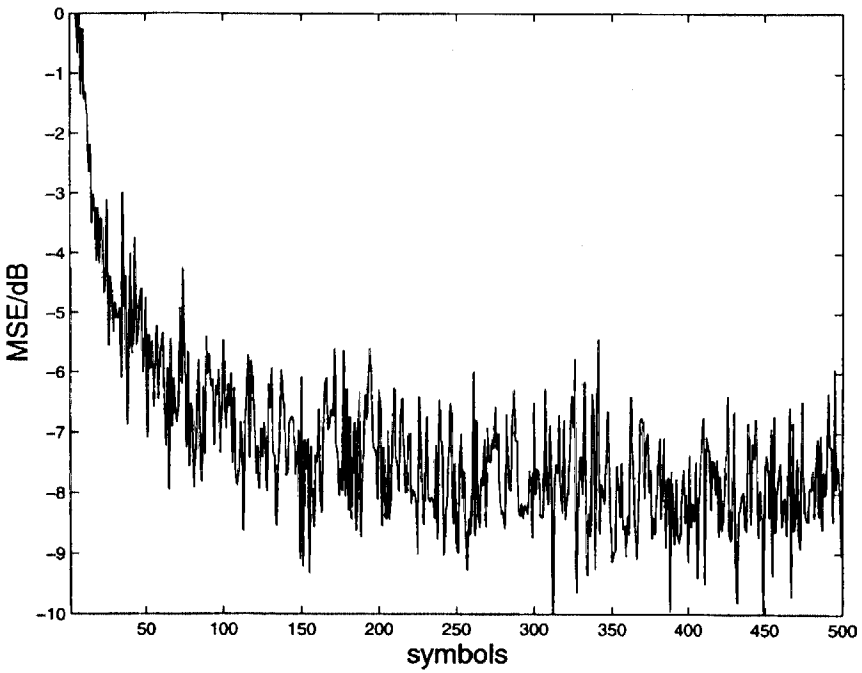


MSE of Parallel Receiver (4 Subbands)

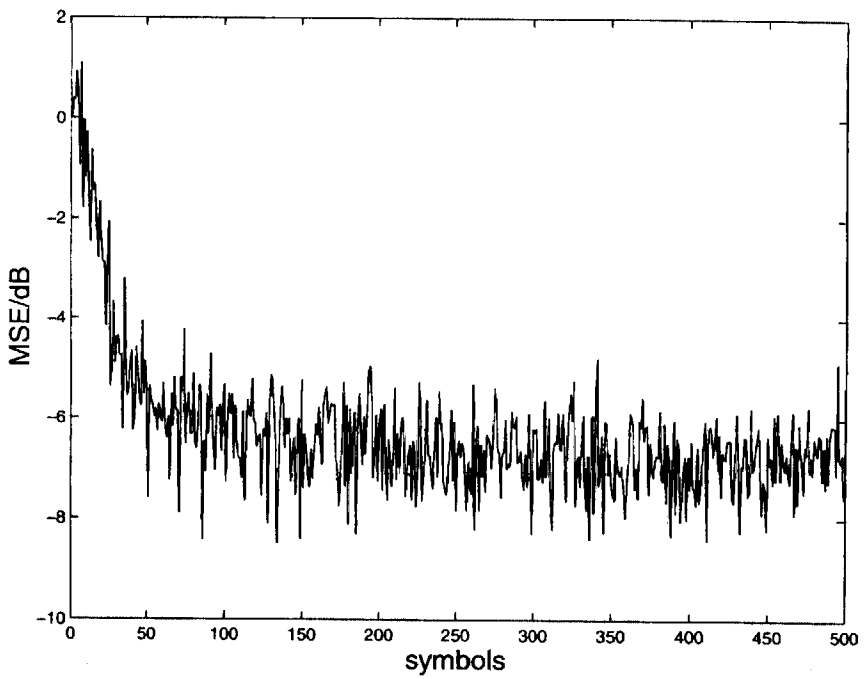


MSE of Parallel Receiver (8 Subbands)

Comparison of Serial and Parallel Receiver by Simulation using RLS (cont.)



MSE of Parallel Receiver (4 Subbands)



MSE of Parallel Receiver (8 Subbands)

Remarks to RLS Simulation

- With RLS, parallel receiver converges faster compared to serial receiver due to shorter filter length
- Observations
  - Factor δ, which scales initial correlation matrix is chosen much bigger than usual for convergence
  - Furthermore δ allows tradeoff between convergence speed and BER, similar to step size of LMS/NLMS
  - Set forgetting factor, $\lambda = 1$ (infinite memory) for best performance
  - Adaptive gain factors have little effect

Part III: Analysis of Parallel Adaptive DSSS Receiver

Optimal Transform Design: General Approach

- We now explore how to design a general transform, **T** for better performance (better BER, faster convergence)
- Calculate MSE at receiver output assuming subband filters have converged to their Wiener solutions, i.e. MMSE
  - Assuming error signal after convergence is white and Gaussian (common assumption), BER follows directly from MSE

$$J_{\min} = \frac{1}{d^2} \sum_{m=1}^{M} \sum_{n=1}^{M} \alpha_m \alpha_n [d_m d_n - (|\, d_m \,|\, \mathbf{w}_{\text{opt},n}^{\text{T}} \mathbf{s}_n + |\, d_n \,|\, \mathbf{w}_{\text{opt},m}^{\text{T}} \mathbf{s}_m) + \mathbf{w}_{\text{opt},m}^{\text{T}} \mathbf{R}_{mn} \mathbf{w}_{\text{opt},n}^{\text{T}}]$$

- Formula gives MMSE for arbitrary transforms and inputs
  - Entries of **T** are wrapped up inside **s, R**
- Not suitable for minimization of MSE with respect to entries of the **T**, i.e. transform optimization is difficult

Optimization of Transform, **T** for Maximum Output SNR (AWGN case)

- Calculate and *maximize* SNR at receiver output, and compute rows of optimal **T**
- Major steps of calculation, shown for case of two subbands with subband filters of length two:

$$\text{SNR} = \frac{P_S}{P_N} = \frac{[(\mathbf{s}_1^T \mathbf{s}_1)\alpha_1 d + (\mathbf{s}_2^T \mathbf{s}_2)\alpha_2 d]^2}{\sigma^2[(\mathbf{s}_1^T \mathbf{s}_1)(t_{11}^2 + t_{12}^2)\alpha_1^2 + (\mathbf{s}_2^T \mathbf{s}_2)(t_{21}^2 + t_{22}^2)\alpha_2^2]}$$

- Assume absolute value of all elements of pulse-shaped PN sequence and **T** are less than 1:

$$\text{SNR} > \frac{[(\mathbf{s}_1^T \mathbf{s}_1)\alpha_1 d + (\mathbf{s}_2^T \mathbf{s}_2)\alpha_2 d]^2}{8\sigma^2[(t_{11}^2 + t_{12}^2)\alpha_1^2 + (t_{21}^2 + t_{22}^2)\alpha_2^2]}$$

Optimization of Transform, **T** for Maximum Output SNR (cont.)

- Constrain SNR denominator to be constant

$$(t_{11}^2 + t_{12}^2)\alpha_1^2 + (t_{21}^2 + t_{22}^2)\alpha_2^2 = k$$

- Assuming BPSK, drop square in SNR numerator
- Use method of Lagrange multipliers to solve constrained optimization problem

$$\nabla f(\mathbf{t}) = \lambda \nabla g(\mathbf{t})$$

$$f(\mathbf{t}) = (\mathbf{s}_1^T \mathbf{s}_1)\alpha_1 d + (\mathbf{s}_2^T \mathbf{s}_2)\alpha_2 d$$

$$g(\mathbf{t}) = (t_{11}^2 + t_{12}^2)\alpha_1^2 + (t_{21}^2 + t_{22}^2)\alpha_2^2$$

Optimization of Transform, **T** for Maximum Output SNR (cont.)

- Solution: Rows of the optimal transform matrix, are the eigenvectors of

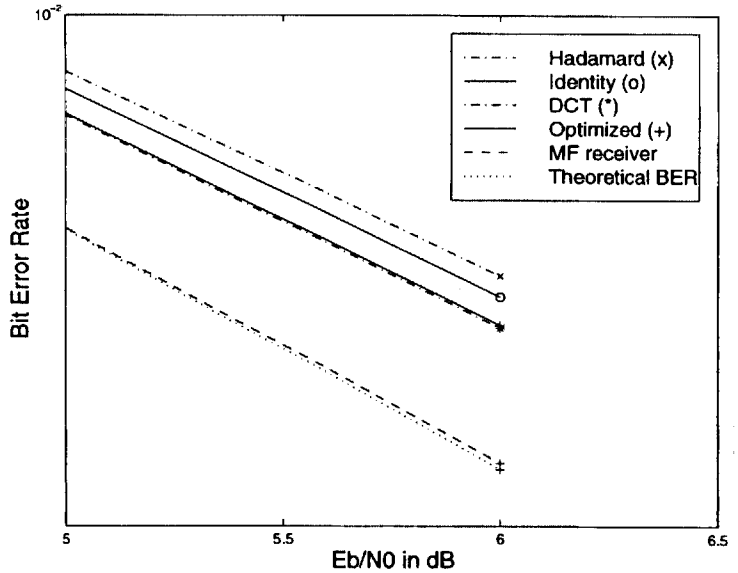
$$\mathbf{B} = \begin{bmatrix} s_1^2 + s_3^2 & s_1 s_2 + s_3 s_4 \\ s_1 s_2 + s_3 s_4 & s_2^2 + s_4^2 \end{bmatrix}$$

- For the general case of M subbands with subband filter length N, entries of **B** are given by

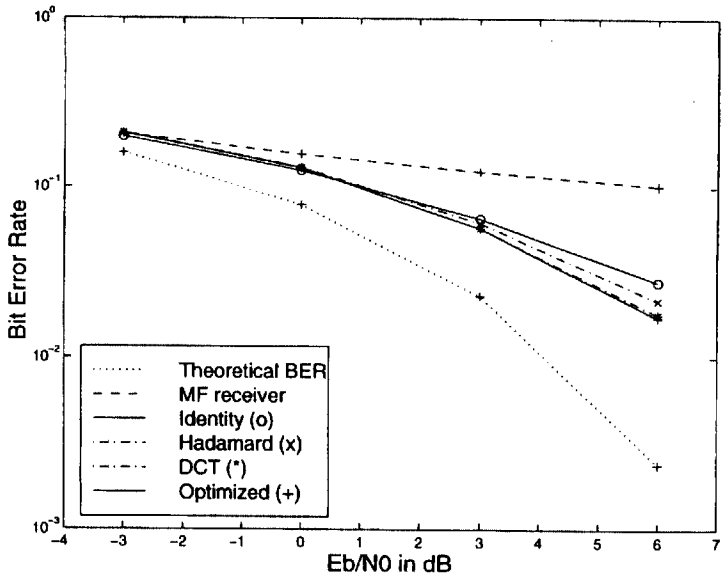
$$b_{mn} = \sum_{i=1}^{M} s_{(i-1)M+m} s_{(i-1)M+n}$$

Performance Comparison of Parallel Receiver Using Different Transforms

- Optimized transform yields slightly better BER
  - Better performance also for interference case, despite the fact derivation was done for AWGN



AWGN case



Interference case

Optimization of Transform, **T** for Fast Convergence

- Analyze how transform, **T** effects convergence speed of receiver
- If LMS or NLMS is used, eigenvalue spread determines convergence speed
- We look at 3 cases
  - Single user
  - Multiuser
  - Sinusoidal interference

Optimization of Transform for Fast Convergence: Single User Case

- For 2 subbands, length 2 subband filter, correlation matrix of subband 1 is:

$$\mathbf{R}_{11} = \begin{bmatrix} (t_{11}s_1 + t_{12}s_2)^2 & (t_{11}s_1 + t_{12}s_2)(t_{11}s_3 + t_{12}s_4) \\ (t_{11}s_1 + t_{12}s_2)(t_{11}s_3 + t_{12}s_4) & (t_{11}s_3 + t_{12}s_4)^2 \end{bmatrix} + \sigma^2(t_{11}^2 + t_{12}^2)\mathbf{I}$$

$$\frac{\lambda_{\max}}{\lambda_{\min}} = \frac{(t_{11}s_1 + t_{12}s_2)^2 + (t_{11}s_3 + t_{12}s_4)^2 + \sigma^2(t_{11}^2 + t_{12}^2)}{\sigma^2(t_{11}^2 + t_{12}^2)}$$

- Optimization for fast convergence (minimization of EV spread) is in *conflict* with optimization for SNR maximization: $(t_{11}s_1 + t_{12}s_2)^2 + (t_{11}s_3 + t_{12}s_4)^2$ is also in numerator of equation for the SNR

Optimization of Transform for Fast Convergence: Multiuser, Sinusoidal Cases

- Can show similar result for multiuser case
- Sinusoidal case is difficult to analyze because of nonstationarity, e.g. correlation matrix time dependent, however, adaptive filter theory assumes stationary processes
- Transform could attenuate sinusoid, however cannot build good notch filter given the transform sizes of interest, e.g. $M < 16$

Computational Costs

- For LMS/NLMS, cost of updating subband filters is similar for serial receiver (because in both cases update at symbol rate)
- For RLS, we have computational savings because costs for RLS update proportional N^2.
  - Fast RLS not usable according to Miller, 1995
- Further computational savings possible by removing subbands which contain only noise
- In all cases need to consider overhead of transform
- Gain factors add very little additional computation

Comparison of Parallel Receivers: Polyphase-Based and Transform-Based

- Advantages of transform-based parallel receiver
  - Computational savings
  - Moderate increase of convergence speed compared to serial receiver with NLMS
  - More significant increase of convergence speed with RLS
- Disadvantages of transform-based parallel receiver
  - Parallel architecture, not fully scalable: for higher number of subbands performance degradation similar to the filterbank architecture

Conclusions

- Architectures for parallel adaptive DSSS receivers have been designed and analyzed
  - Due to parallel nature, we can employ multiple lower speed processing units
- BER performance of parallel receivers close to serial one
  - Novel use of gain factors to speed up convergence
  - Possible increase of convergence speed
  - Possible computational savings
- Future work
  - Synchronization issues, non-square transforms, more realistic channel conditions

EFQPSK versus CERN: A Comparative Study

Presented by

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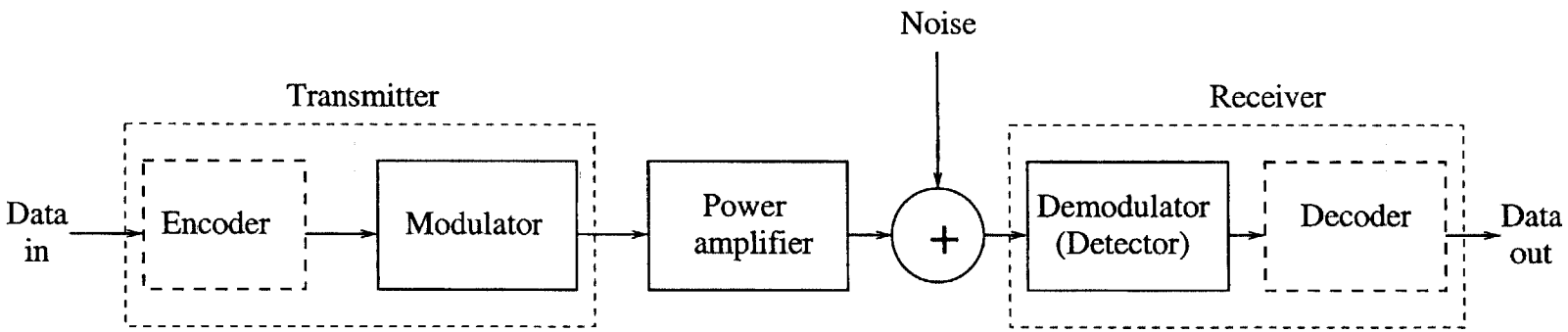
OVERVIEW

- Introduction
- EFQPSK
- CERN
- Numerical Results
- Future Work and Conclusions

Communication System



TWT Amplifier Model

Consider an input signal $x(t) = m(t)\cos(\omega_c t + \psi(t))$, where

- ω_c is the carrier frequency,
- $m(t)$ and $\psi(t)$ are modulated envelope and phase, respectively.

The corresponding TWT output is

$$y(t) = A[m(t)]\cos(\omega_c t + \psi(t) + \Phi[m(t)]) \tag{1}$$

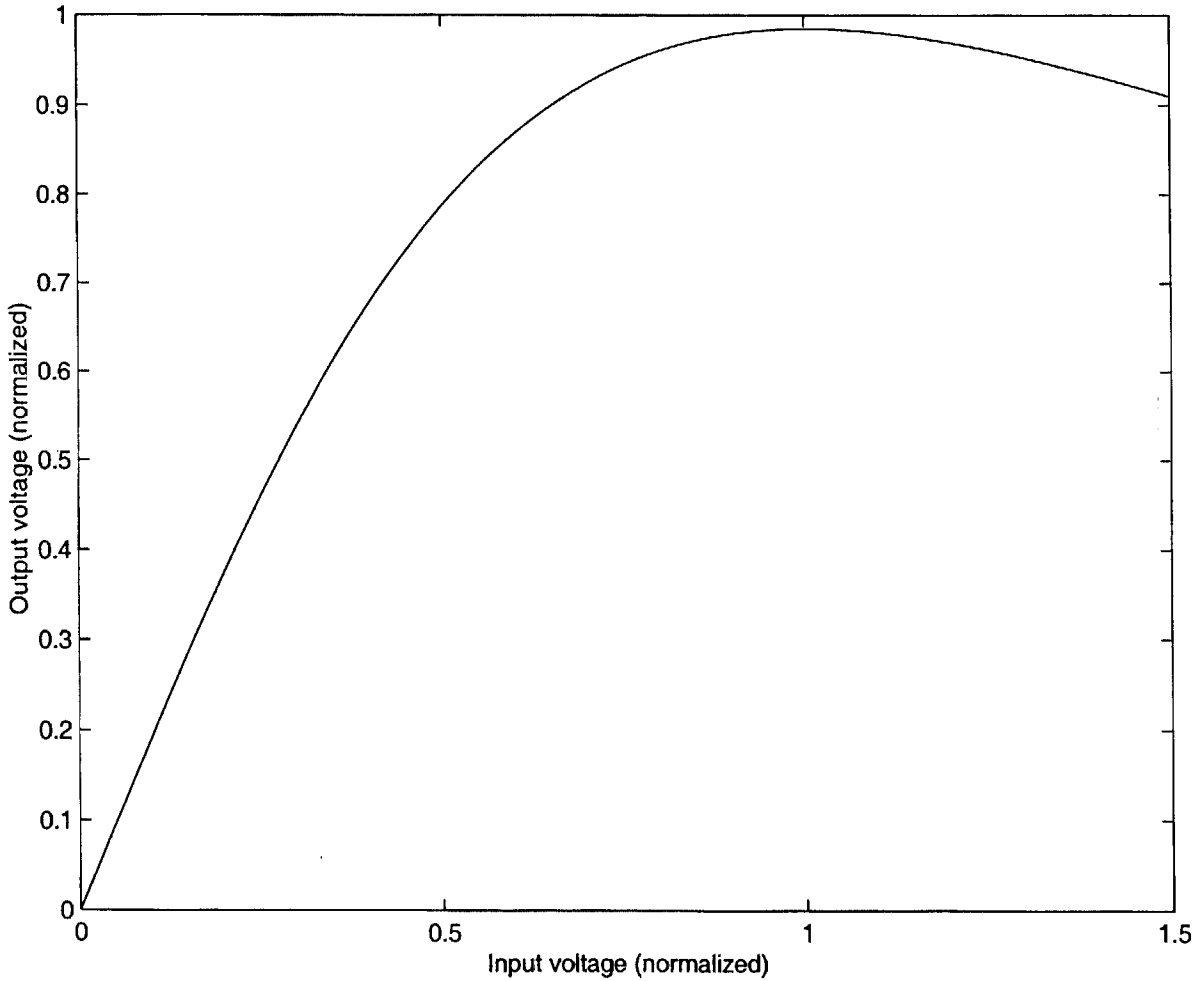
where

$$A(m) = \frac{\alpha_a m}{1 + \beta_a m^2}$$

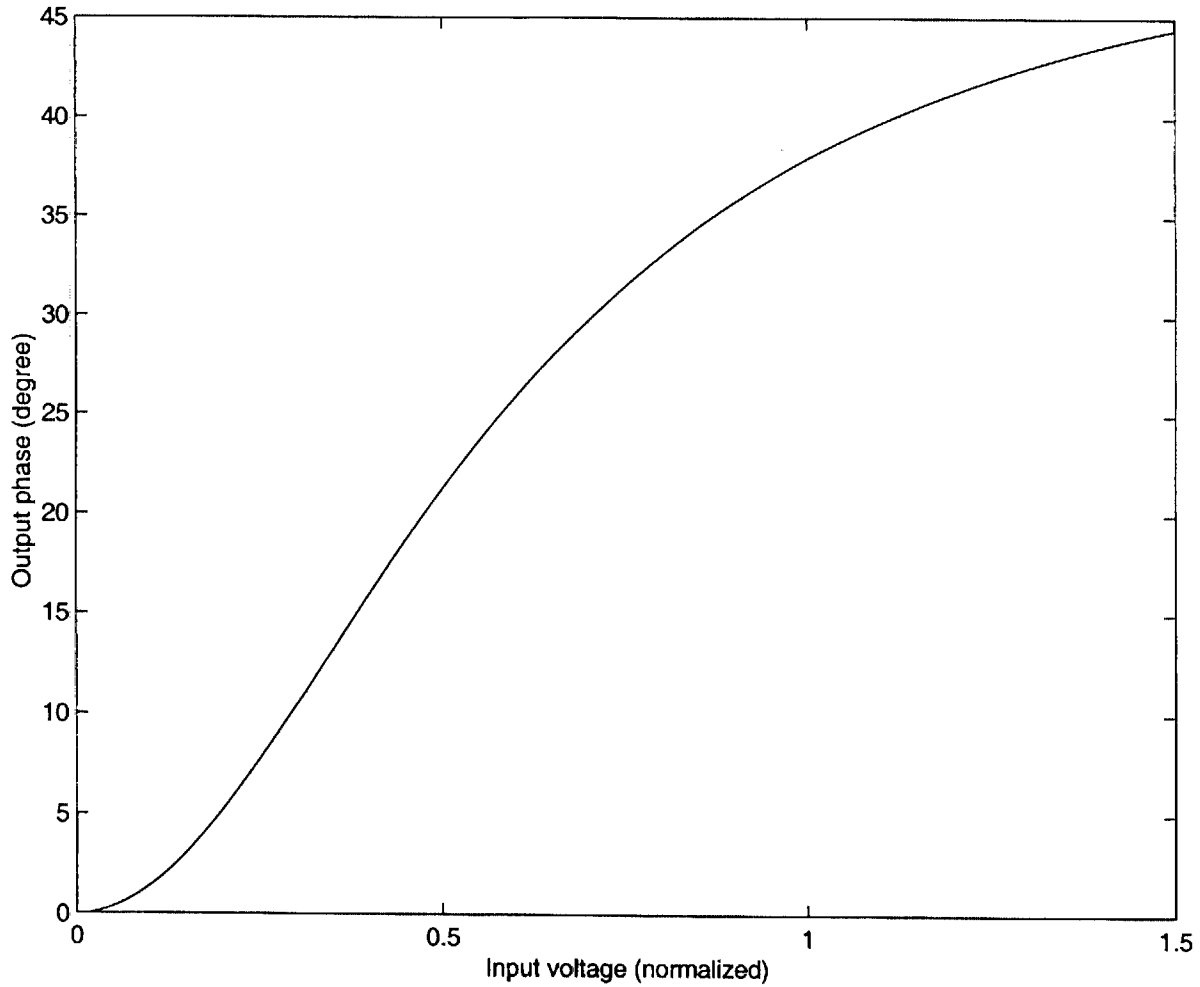
$$\Phi(m) = \frac{\alpha_\phi m^2}{1 + \beta_\phi m^2}$$

We use $\alpha_a = 1.9638$, $\alpha_\phi = 2.5293$, $\beta_a = 0.9945$, and $\beta_\phi = 2.8168$.

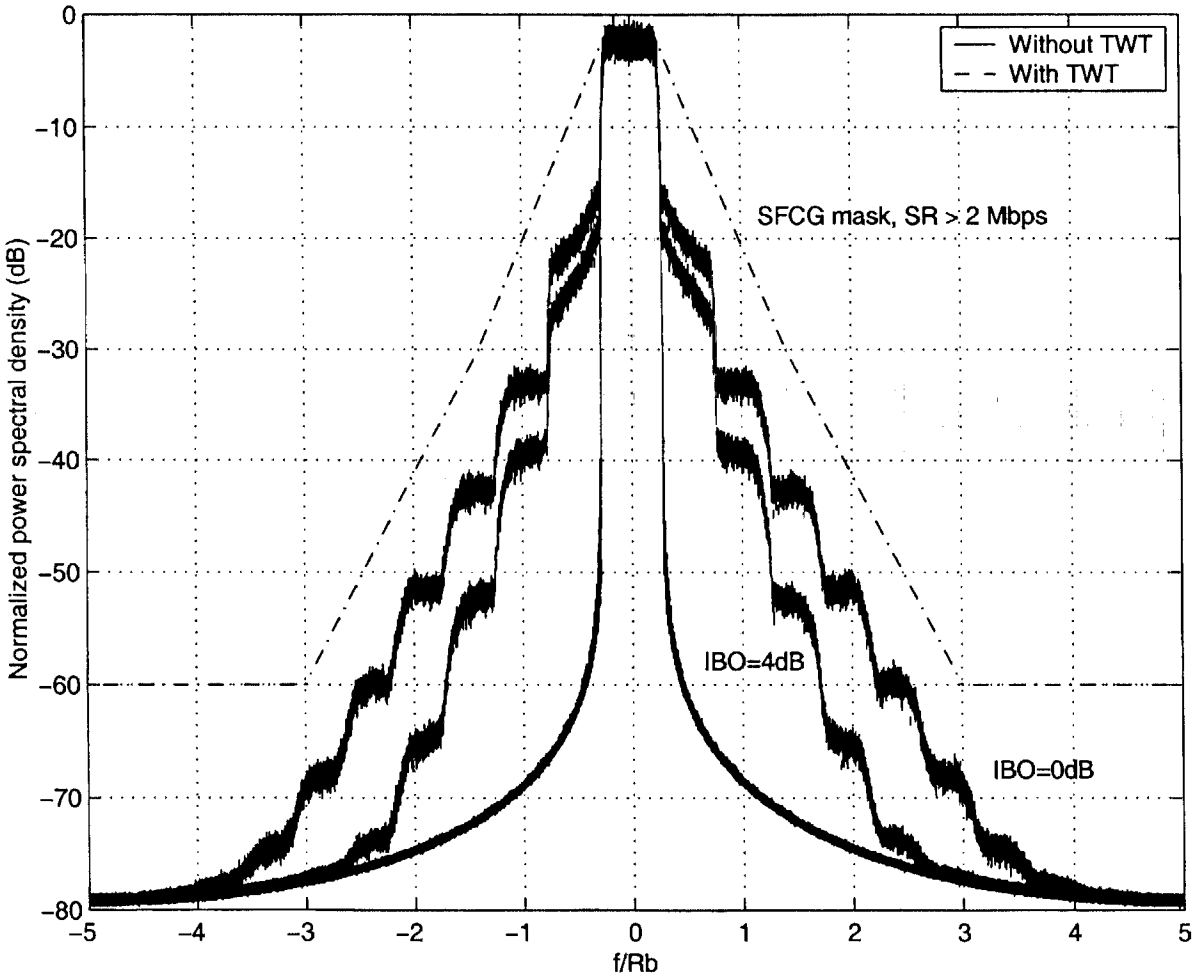
AM/AM Characteristics of a Commercial TWT



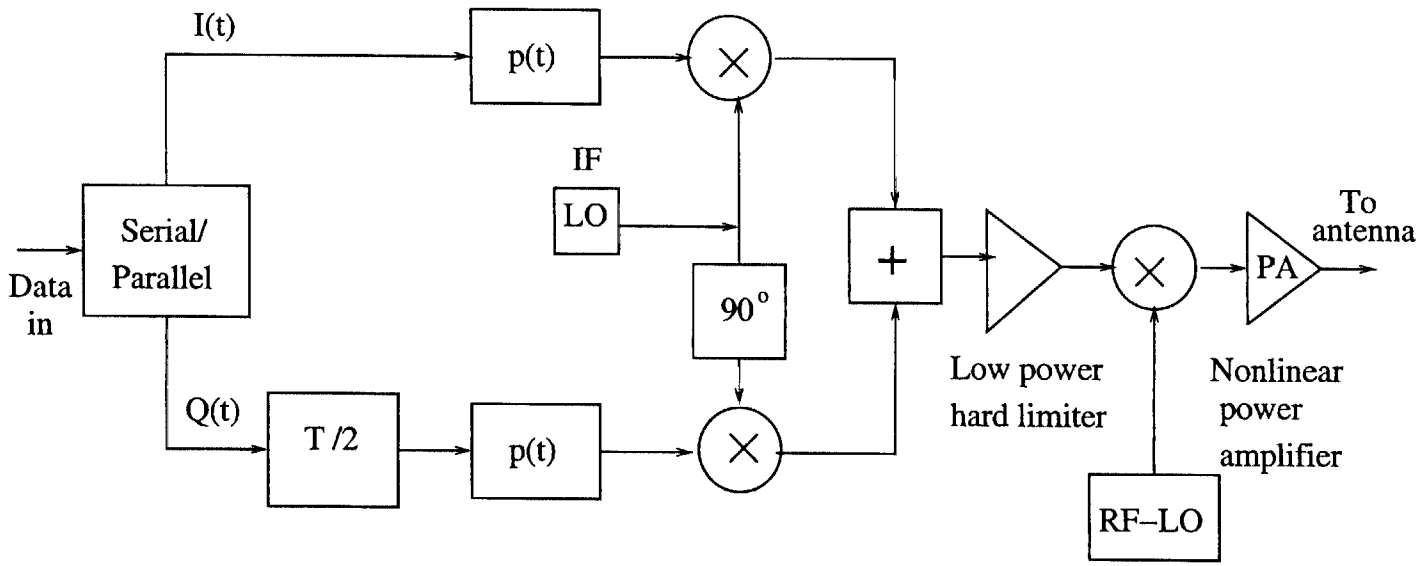
AM/PM Characteristics of a Commercial TWT



Spectra of Conventional RRC Filtered QPSK



FQPSK Block Diagram



Waveform Set of EFQPSK

The constant A is $1/\sqrt{2}$ in the following equations.

1. $s_0(t) = A, \ -T/2 \le t \le T/2, \ \ s_8(t) = -s_0(t)$

2. $$s_1(T) = \begin{cases} A, & -T/2 \le t \le 0 \\ 1-(1-A)\cos^2(\pi t/T), & 0 \le t \le T/2 \end{cases}$$
   $s_9(t) = -s_1(t)$

3. $$s_2(t) = \begin{cases} 1-(1-A)\cos^2(\pi t/T), & -T/2 \le t \le 0 \\ A, & 0 \le t \le T/2 \end{cases}$$
   $s_{10}(t) = -s_2(t)$

4. $s_3(t) = 1-(1-A)\cos^2(\pi t/T), \ -T/2 \le t \le T/2,$
   $s_{11}(t) = -s_3(t)$

Waveform Set of EFQPSK contd.

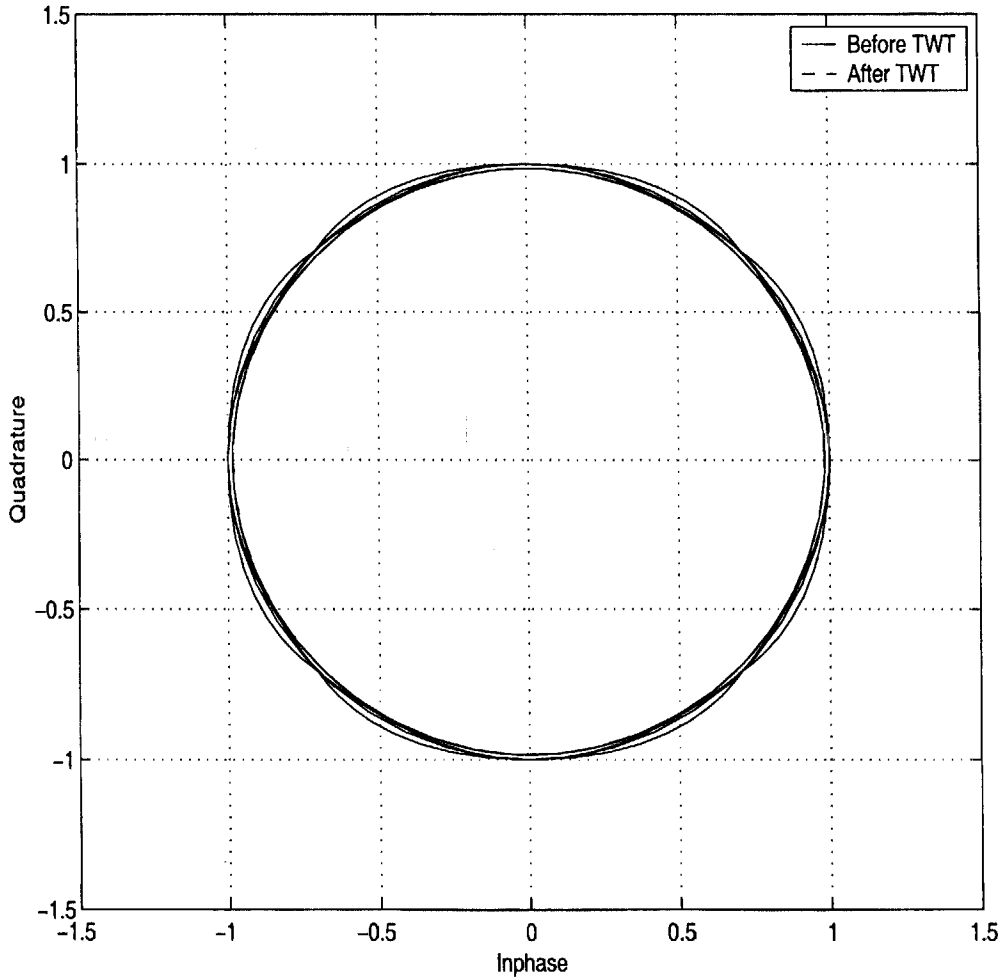
5. $s_4(t) = A\sin(\pi t/T), \quad -T/2 \le t \le T/2, \quad s_{12}(t) = -s_4(t)$

6. $$s_5(t) = \begin{cases} \sin(\pi t/T) + (1-A)\sin^2(\pi t/T), & -T/2 \le t \le 0 \\ \sin(\pi t/T), & 0 \le t \le T/2 \end{cases}$$
$$s_{13}(t) = -s_5(t)$$

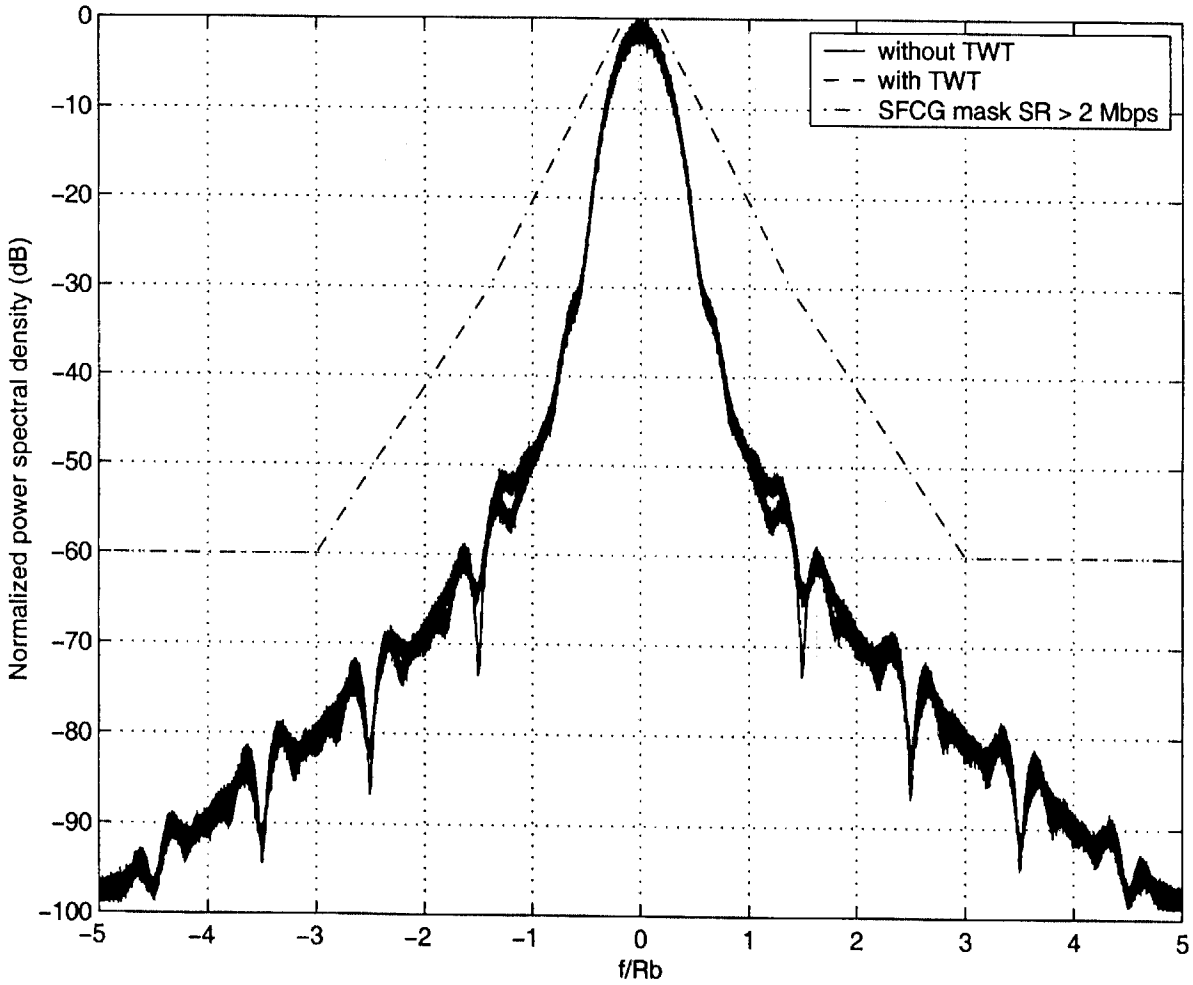
7. $$s_6(t) = \begin{cases} \sin(\pi t/T), & -T/2 \le t \le 0 \\ \sin(\pi t/T) - (1-A)\sin^2(\pi t/T), & 0 \le t \le T/2 \end{cases}$$
$$s_{14}(t) = -s_6(t)$$

8. $s_7(t) = \sin(\pi t/T) \quad -T/2 \le t \le T/2, \quad s_{15}(t) = -s_7(t)$

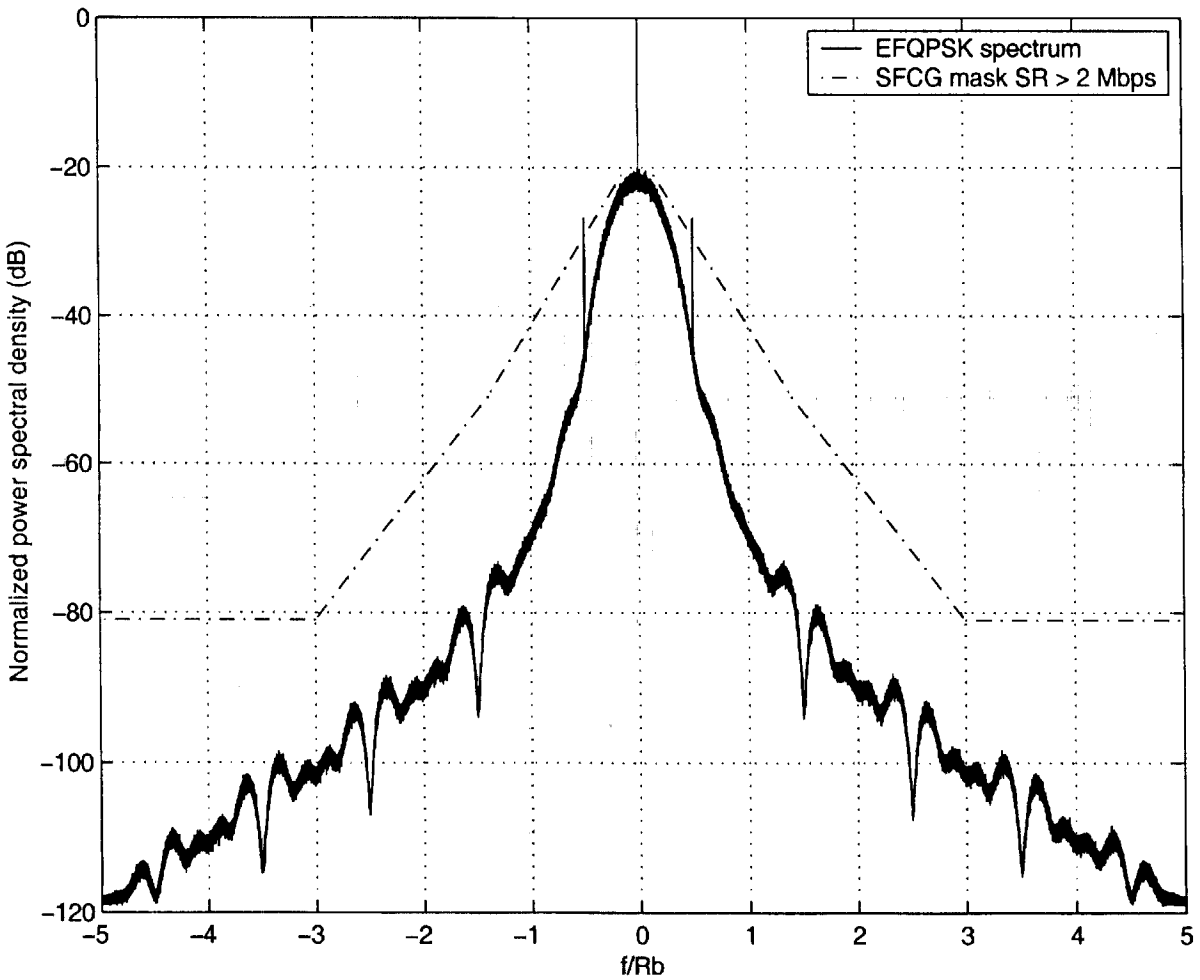
Vector Plot of EFQPSK



Spectra of EFQPSK



Spectra of EFQPSK with Unbalanced Data



Probability of a bit being a +1	Relative strength at zero frequency (dB)	Relative strength at $f = 1/2T_b$ (dB)
0.45	+16.0	-10.0
0.40	+21.0	-4.0
0.35	+25.0	-0.5
0.30	+30.0	0.0
0.25	+30.0	+0.5
0.15	+38.0	+1.5
0.10	+39.0	+2.5
0.05	+41.0	+1.0

Table 1: Line strengths with unbalanced data. The reference spectrum level is zero frequency for balanced data.

Spectra of EFQPSK

Advantages

- Spectrally efficient compared to conventional QPSK under nonlinear amplification.
- Spectral properties remain intact under nonlinear amplification.

Disadvantages

- Not spectrally efficient compared to conventional QPSK under linear amplification.
- Spectral lines are produced when unbalanced data are used.

Constrained Envelope Root Nyquist (CERN)

Consider a baseband equivalent linearly modulated signal $s_o(t)$,

$$s_o(t) = \sum_i a_i p(t - iT)$$

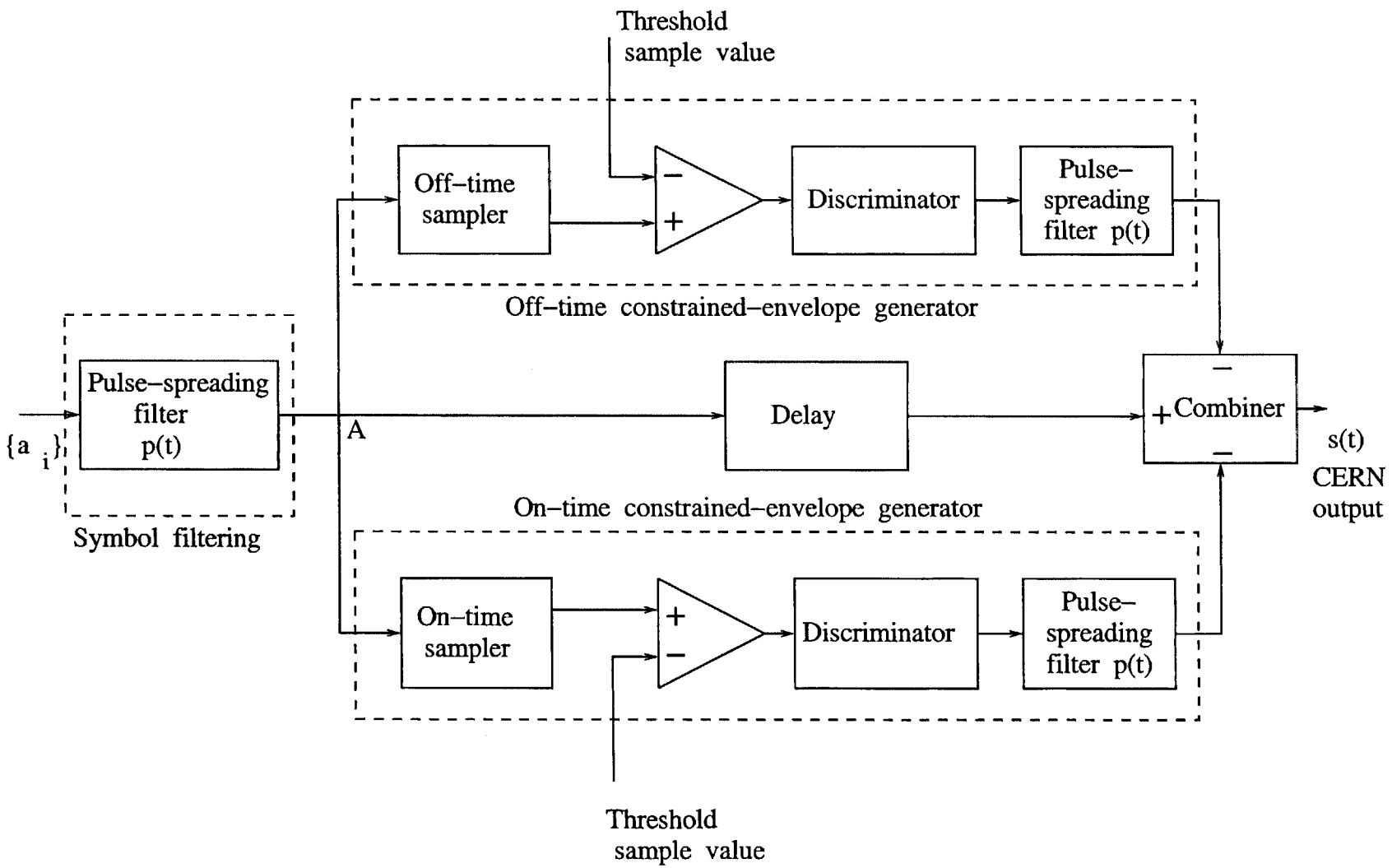
where $\{a_i\}$ is the symbol sequence, $p(t)$ is a pulse-spreading filter, T is the symbol period. Consider a sampling rate of 2 samples per symbol interval at time instants $t = 0T, 0.5T, T, 1.5T, 2T, \cdots$. These are

$$\{s_o(0T), s_o(0.5T), s_o(T), s_o(1.5T), s_o(2T), s_o(2.5T), s_o(3T), \cdots\}$$

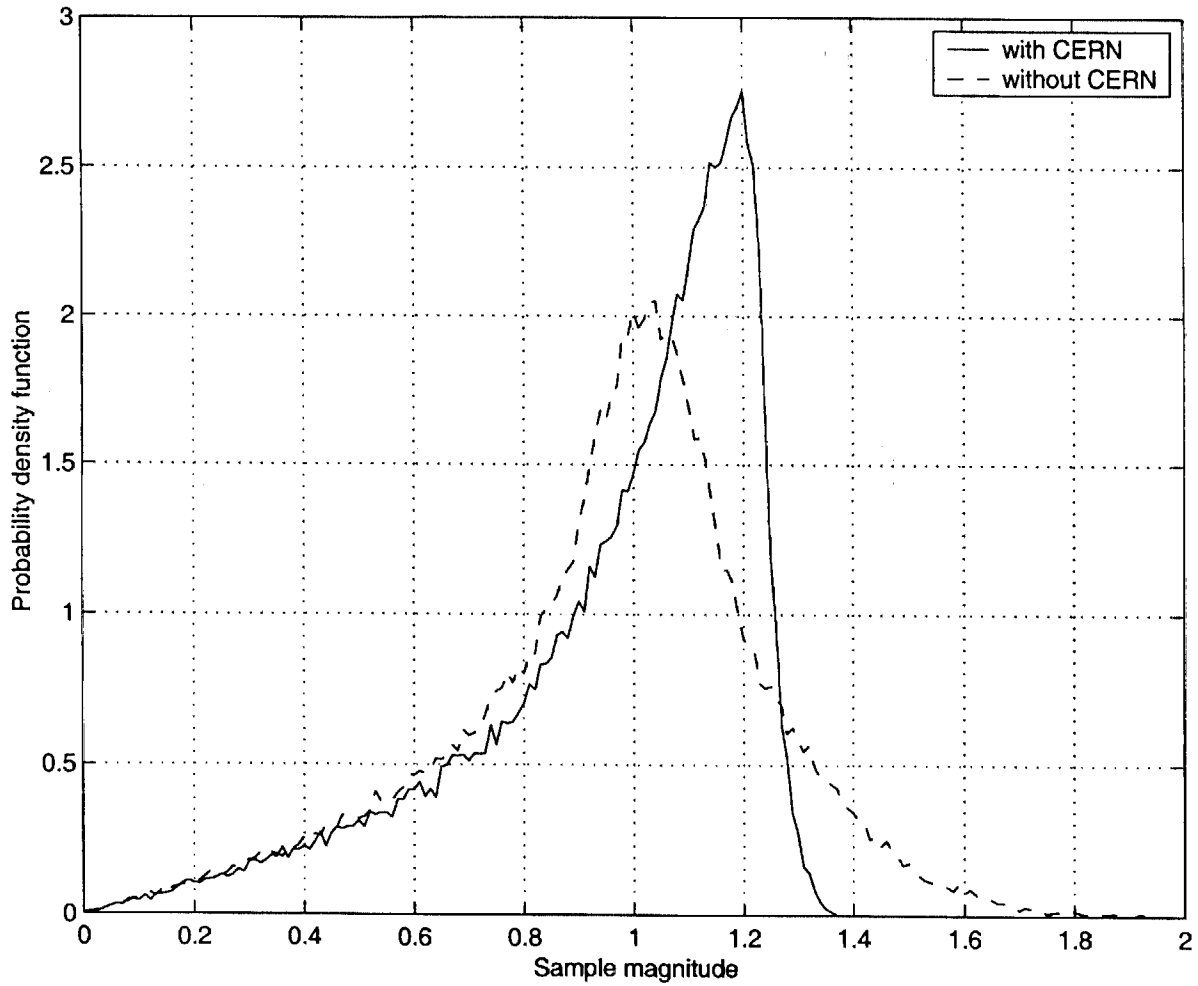
Divide the signal samples into two groups:

- On-time samples: samples at time instants $t = iT$.
- Off-time samples: samples at time instants $t = (i + 0.5)T$.

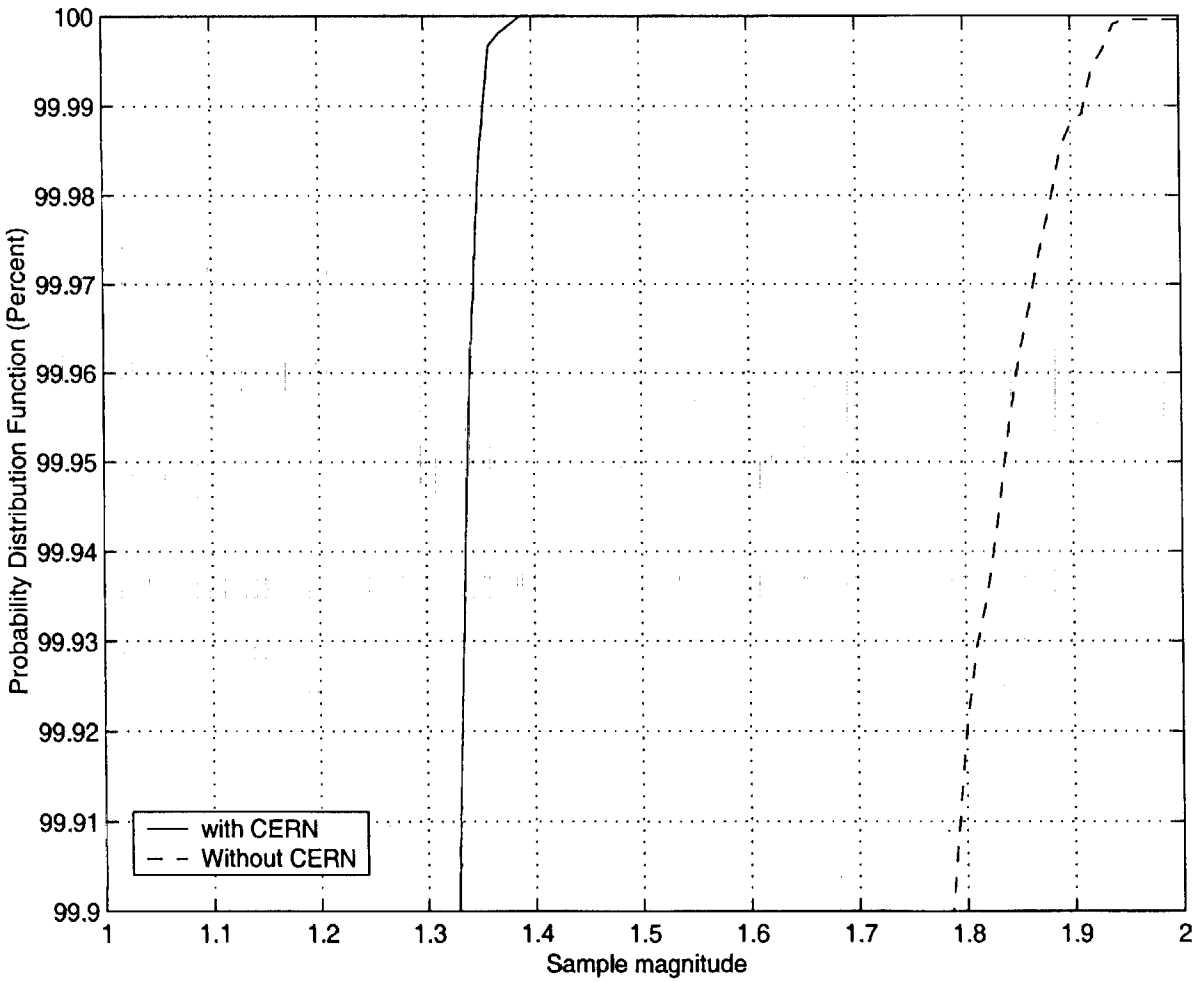
CERN Generation



Magnitude Probability Density Function (8 PSK)



Magnitude Probability Distribution Function



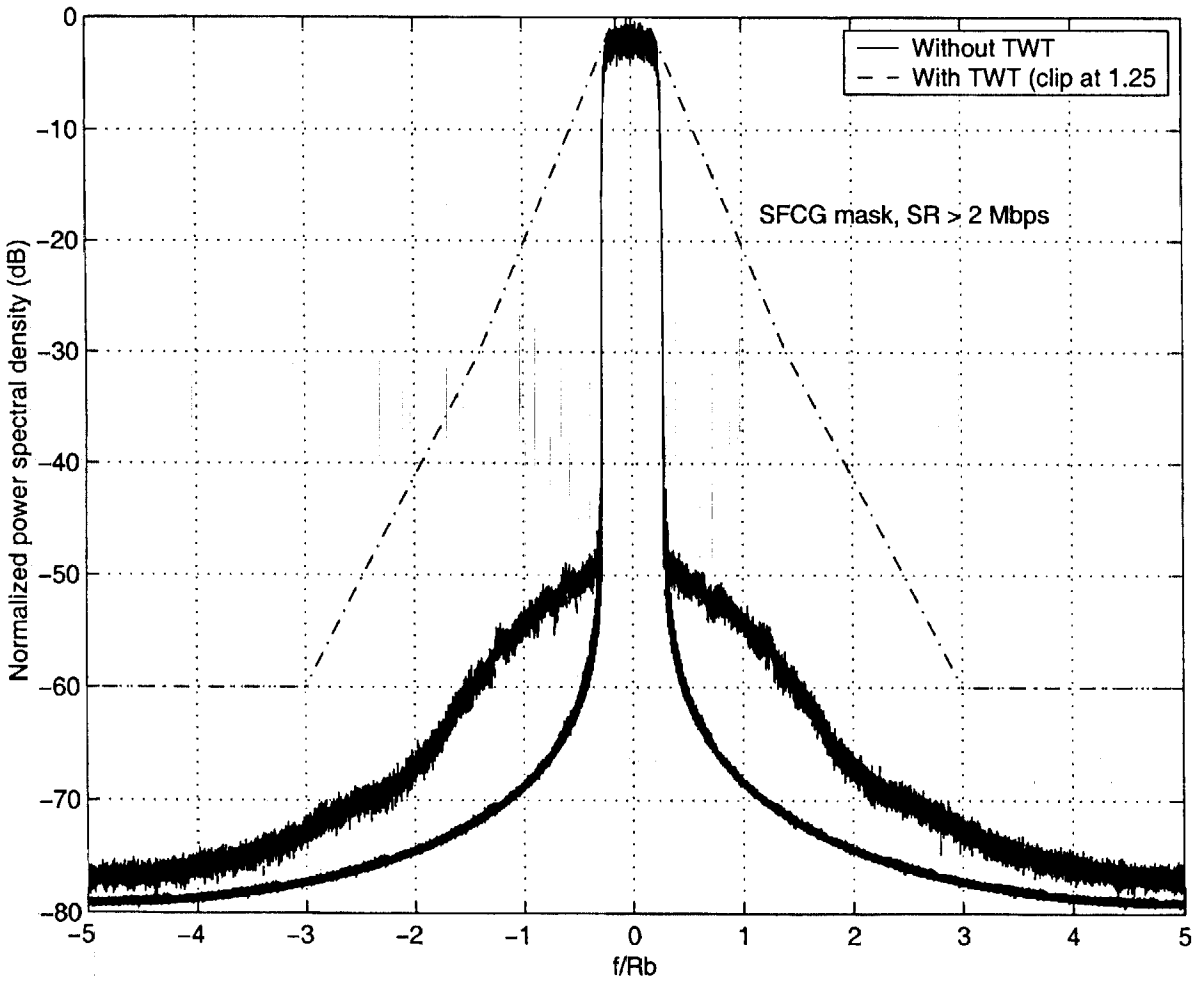
Potential Backoff Improvement

Consider a threshold clipping level of 0.01%.

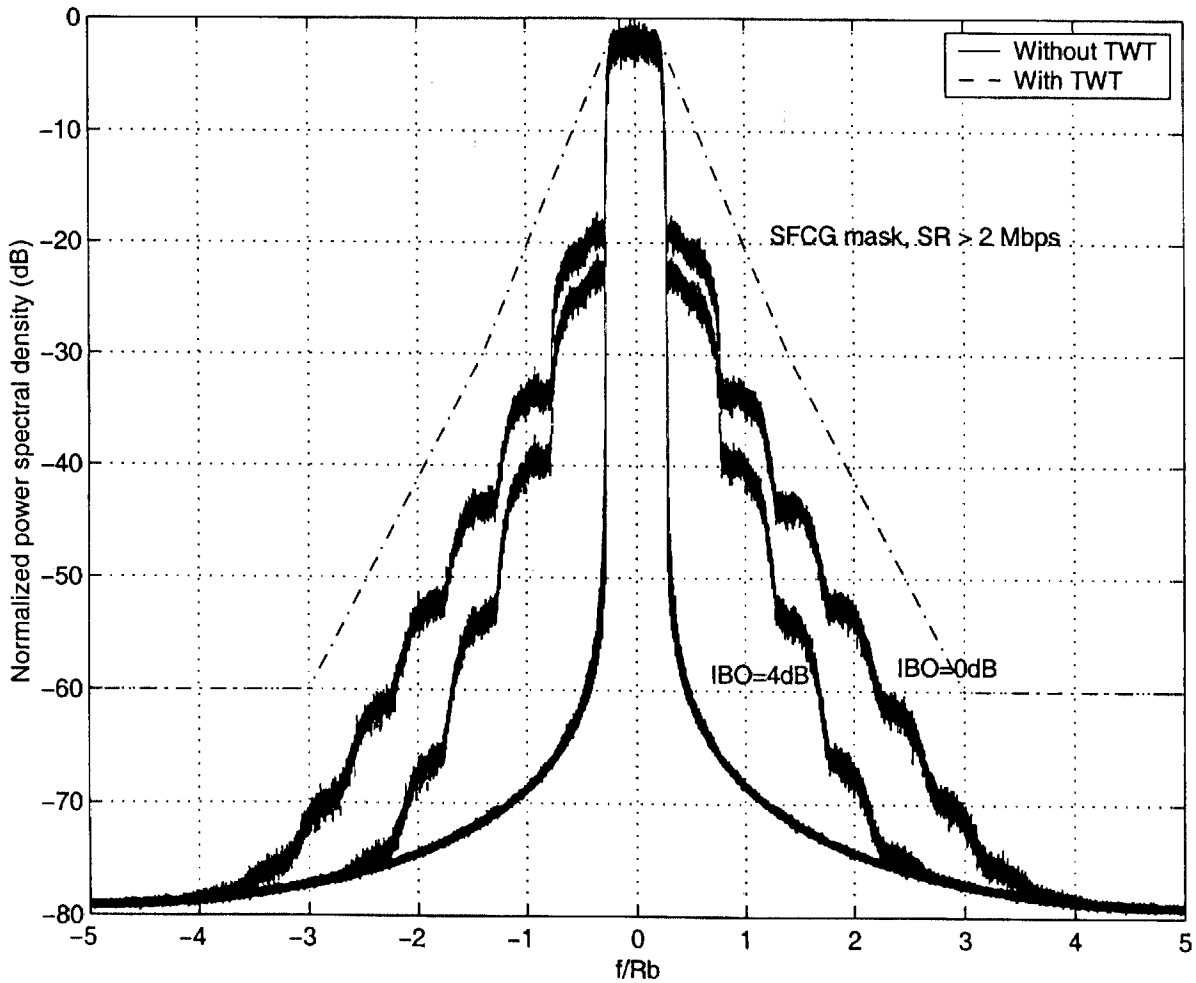
- Conventional 8 PSK: 1.91
- CERN 8 PSK: 1.36

Back off improvement: $20 \log_{10}(1.91/1.36) \approx 2.95$ dB

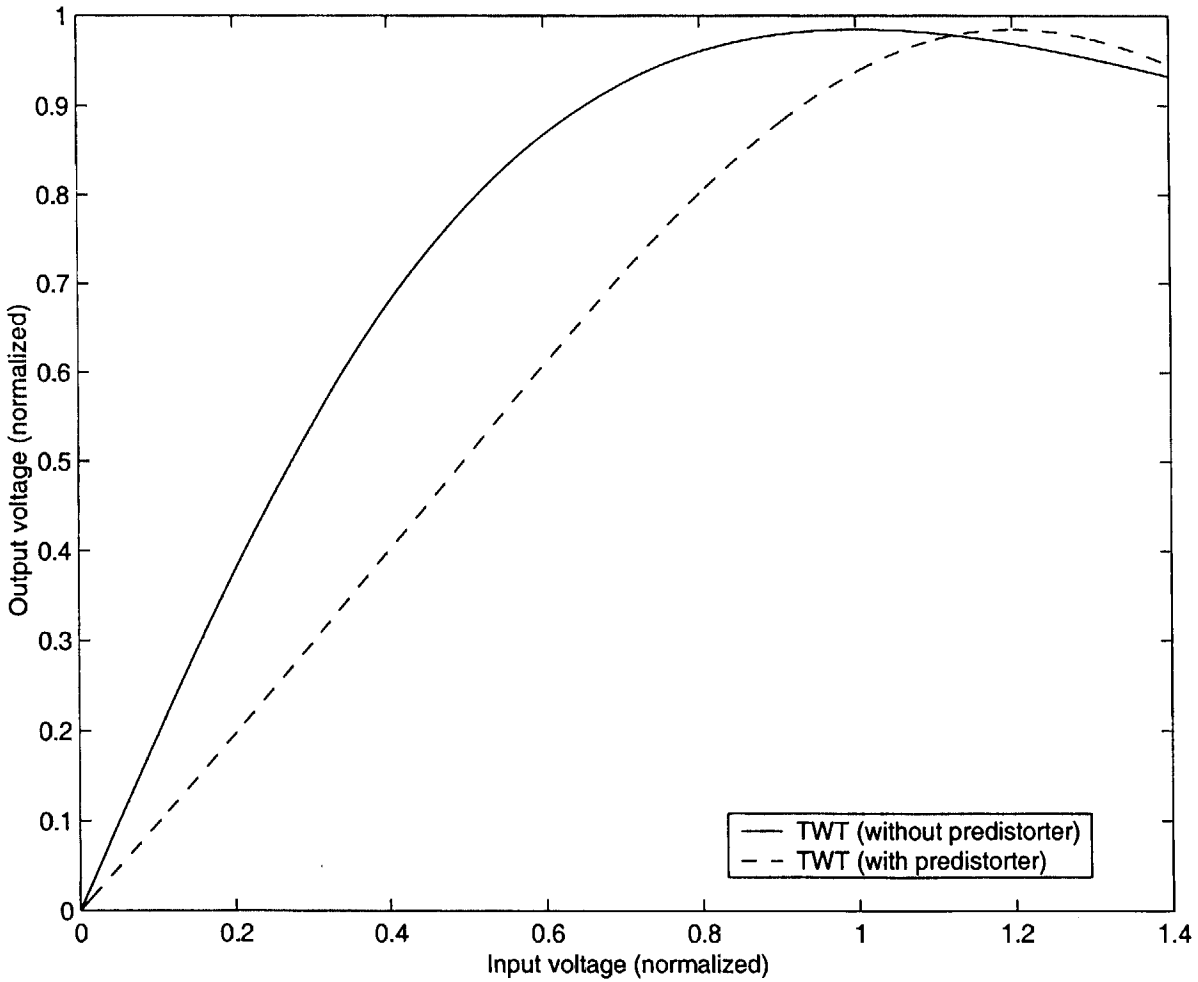
QPSK CERN Spectra with Ideal Clipper



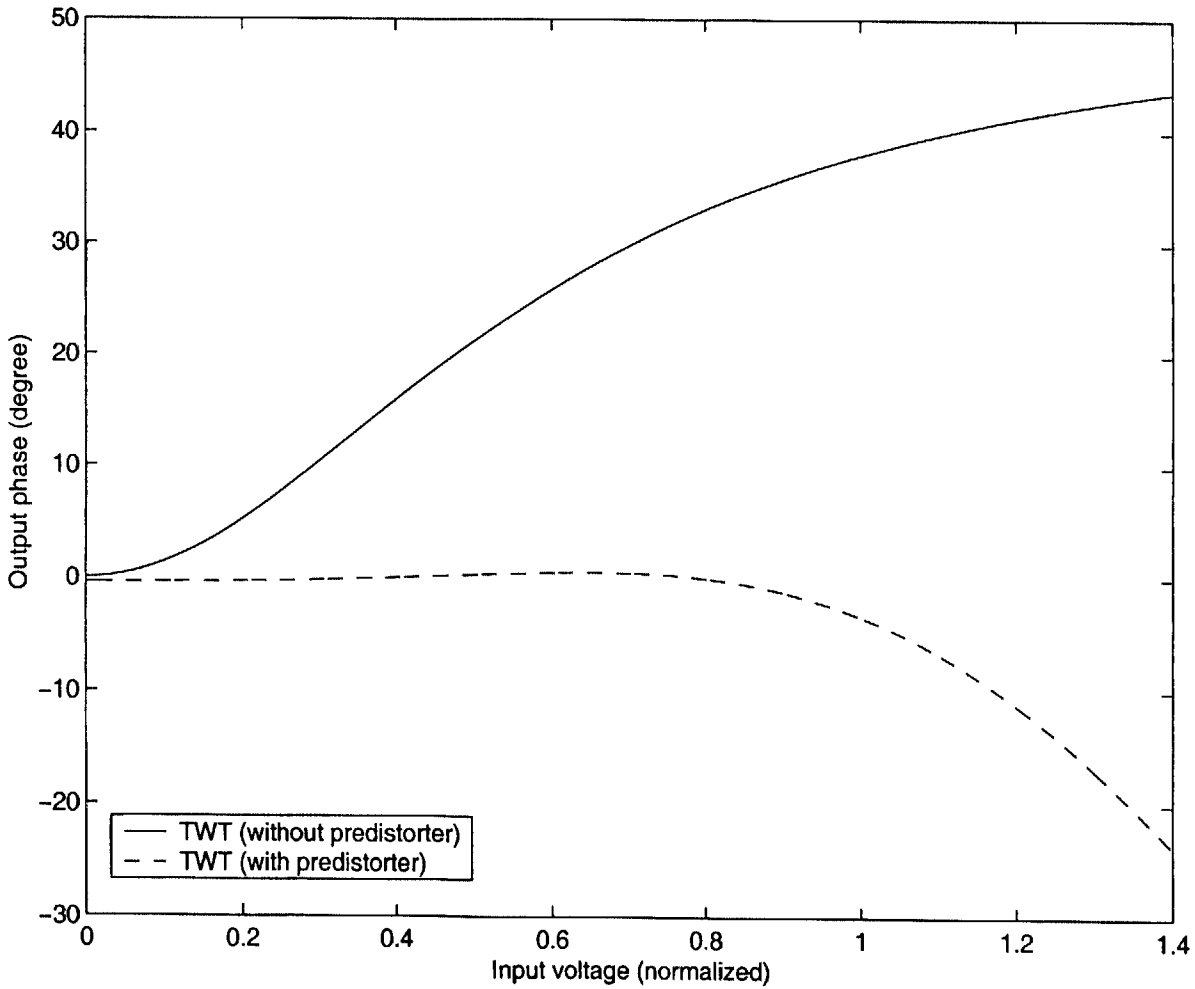
QPSK CERN Spectra with a Commercial TWT



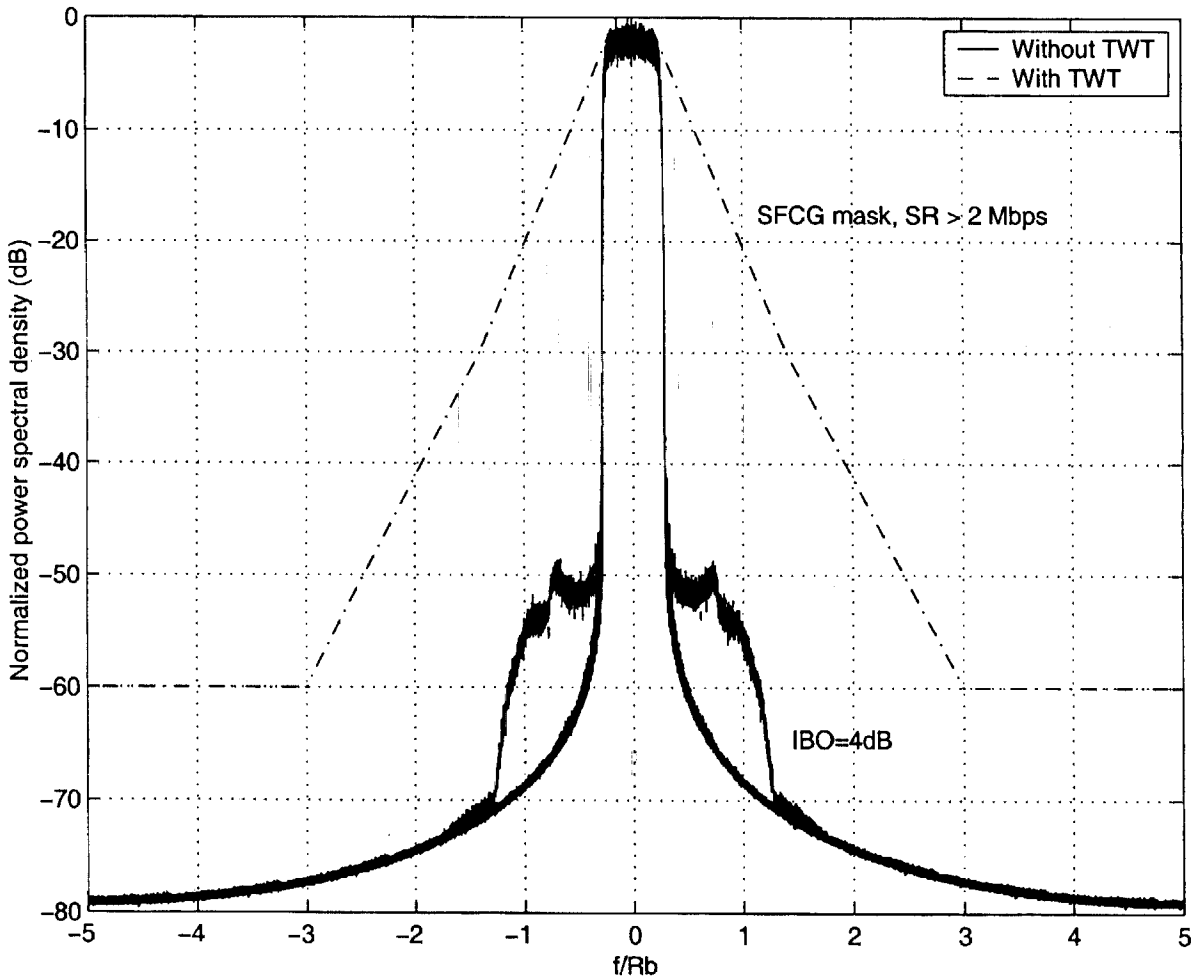
Effect of the Predistorter on AM/AM



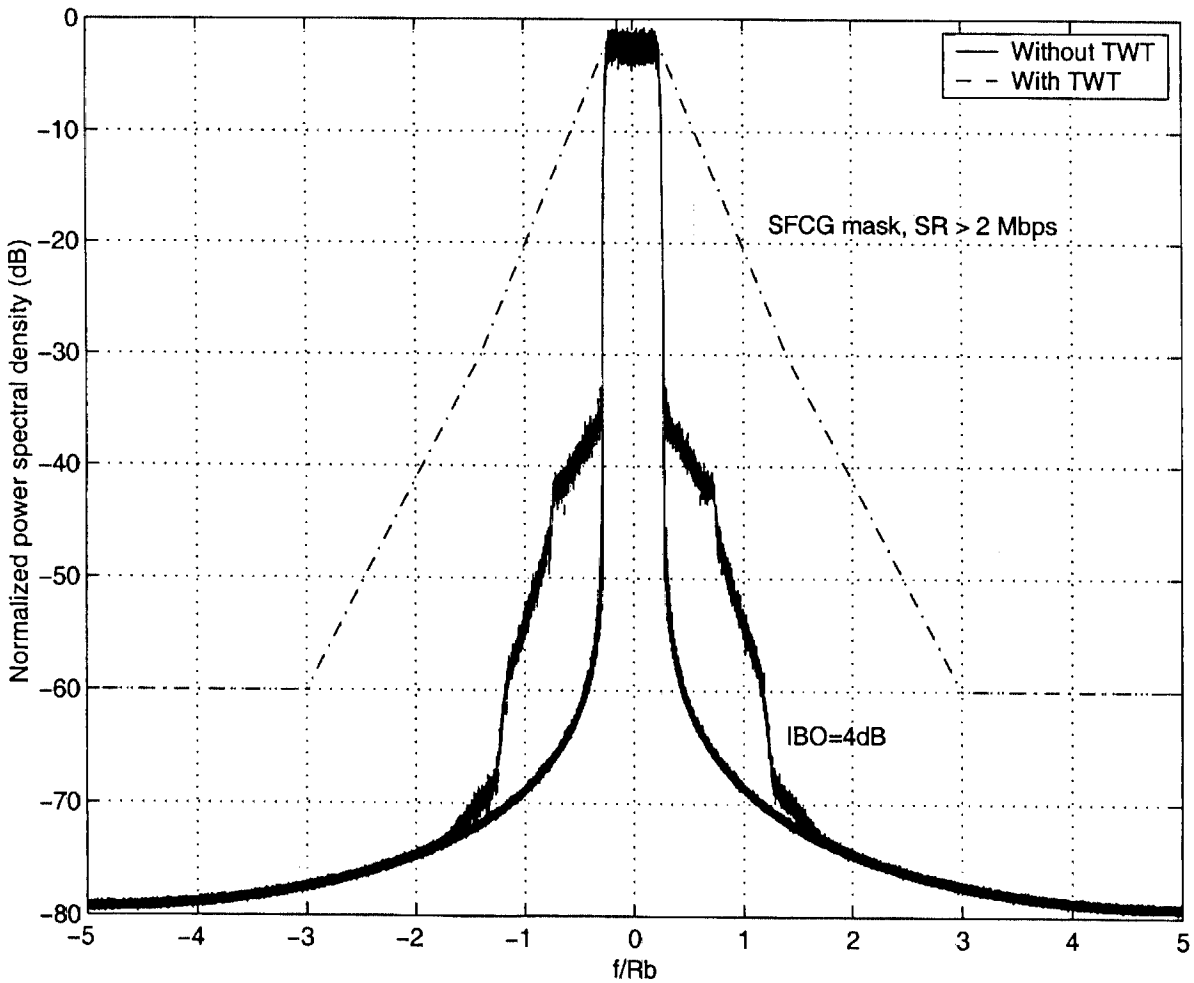
Effect of the Predistorter on AM/PM



QPSK CERN Spectra with Predistorter



Conventional RRC QPSK Spectra with Predistorter



Spectra of CERN

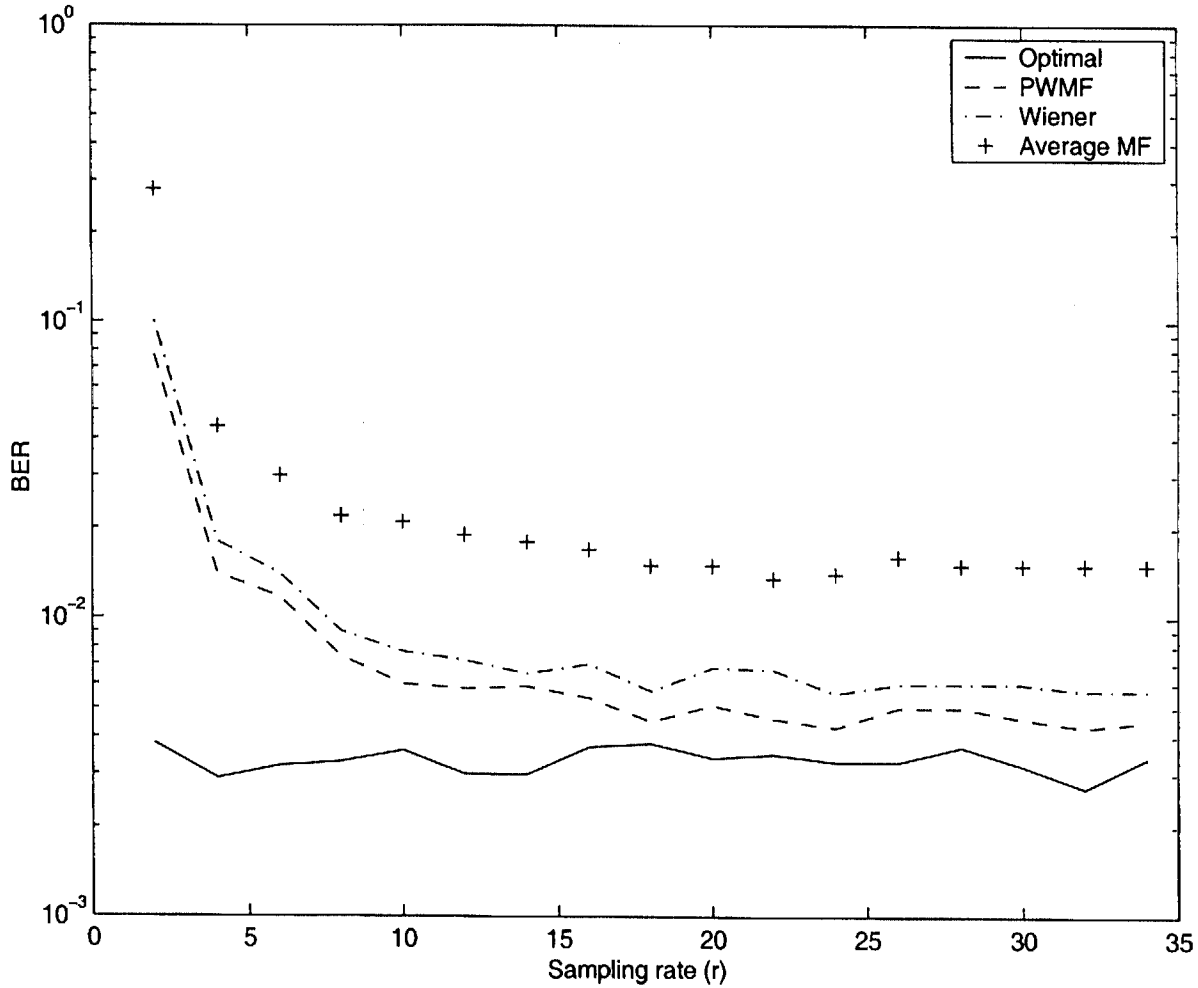
Advantages

- Improves spectral efficiency over conventional QPSK under nonlinear amplification.
- Does not generate spectral lines for unbalanced data (except a DC line).

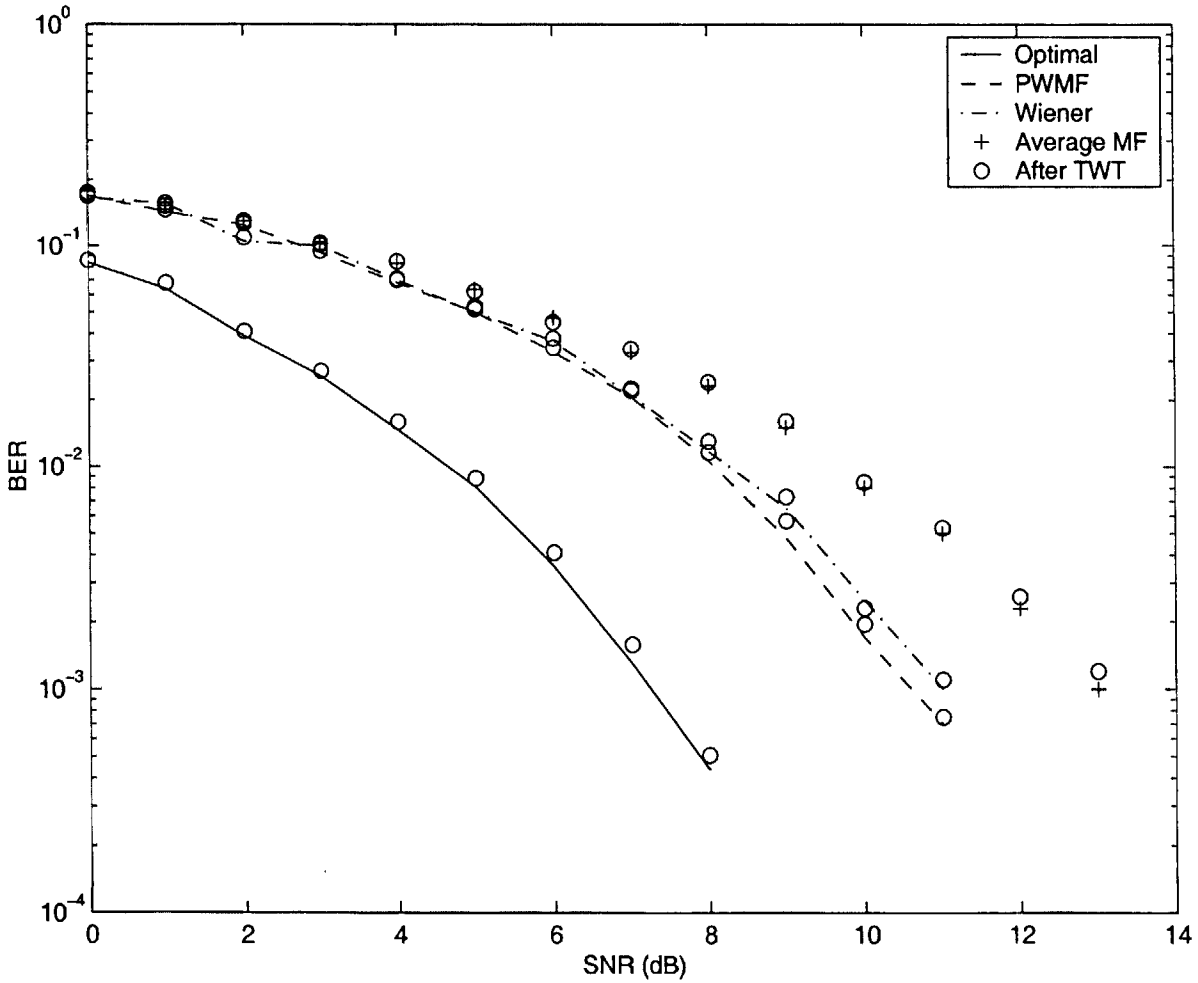
Disadvantages

- Requires a good predistorter, else much less benefit.

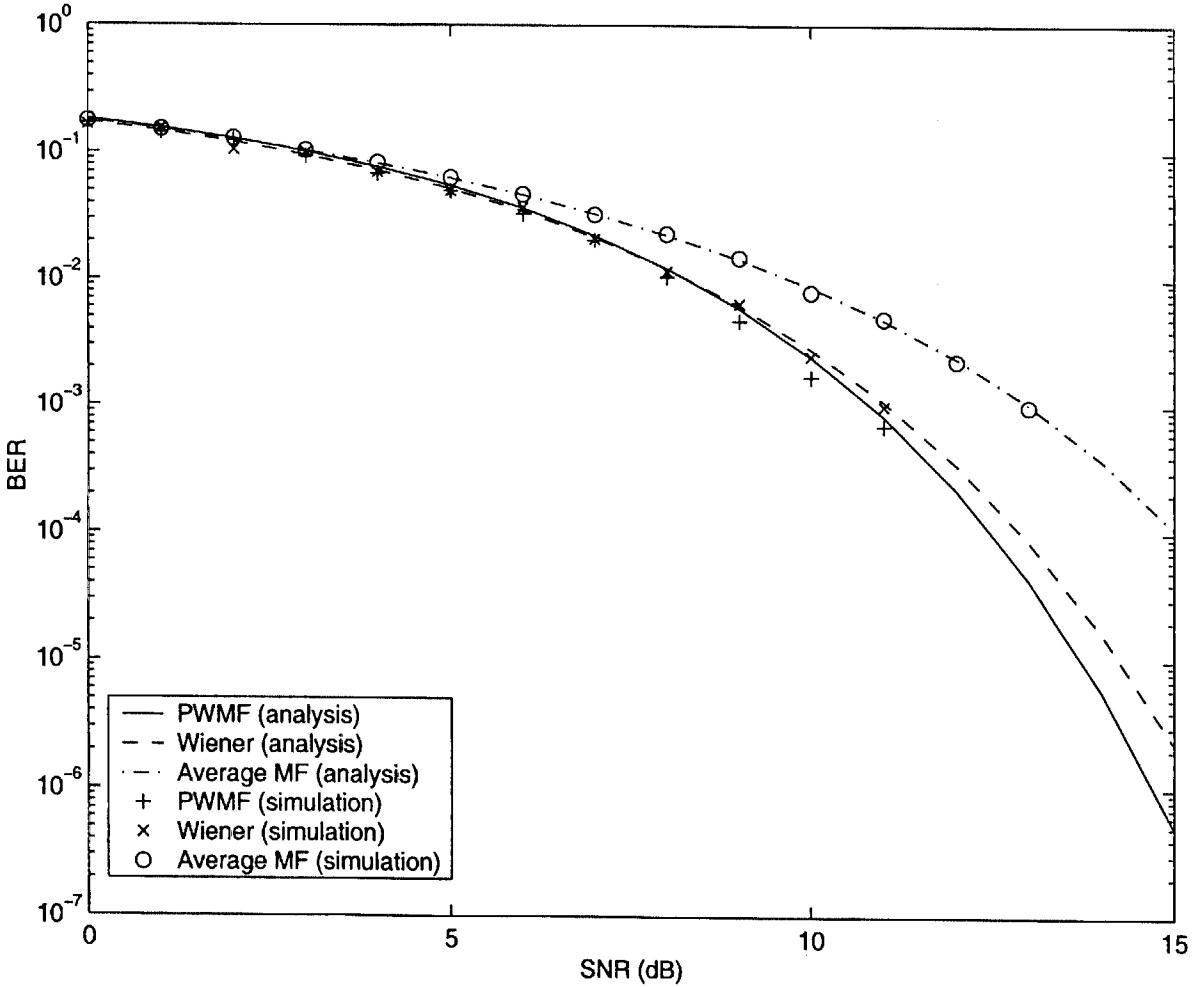
Effect of sampling rate on EFQPSK



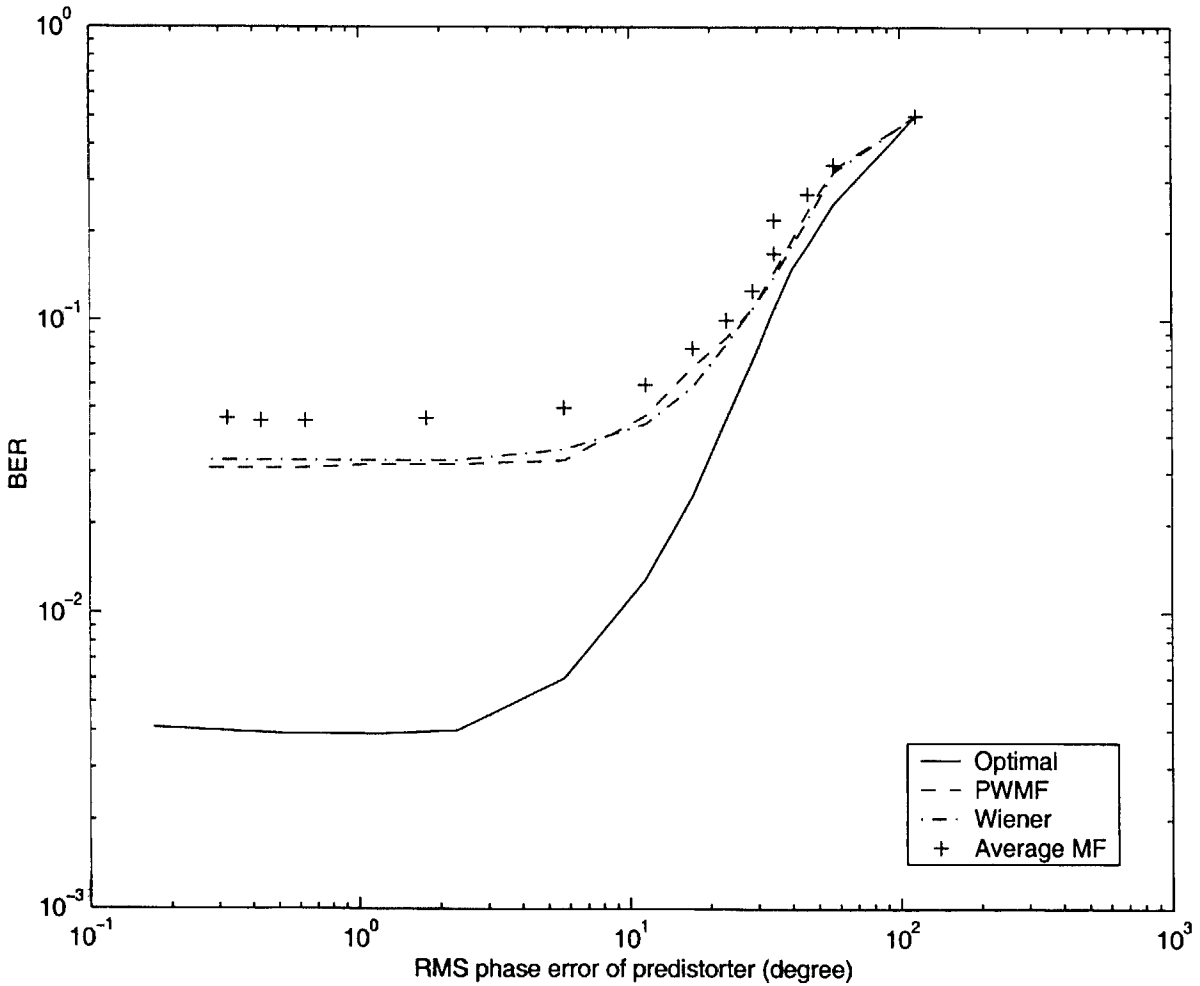
BER performance of uncoded EFQPSK



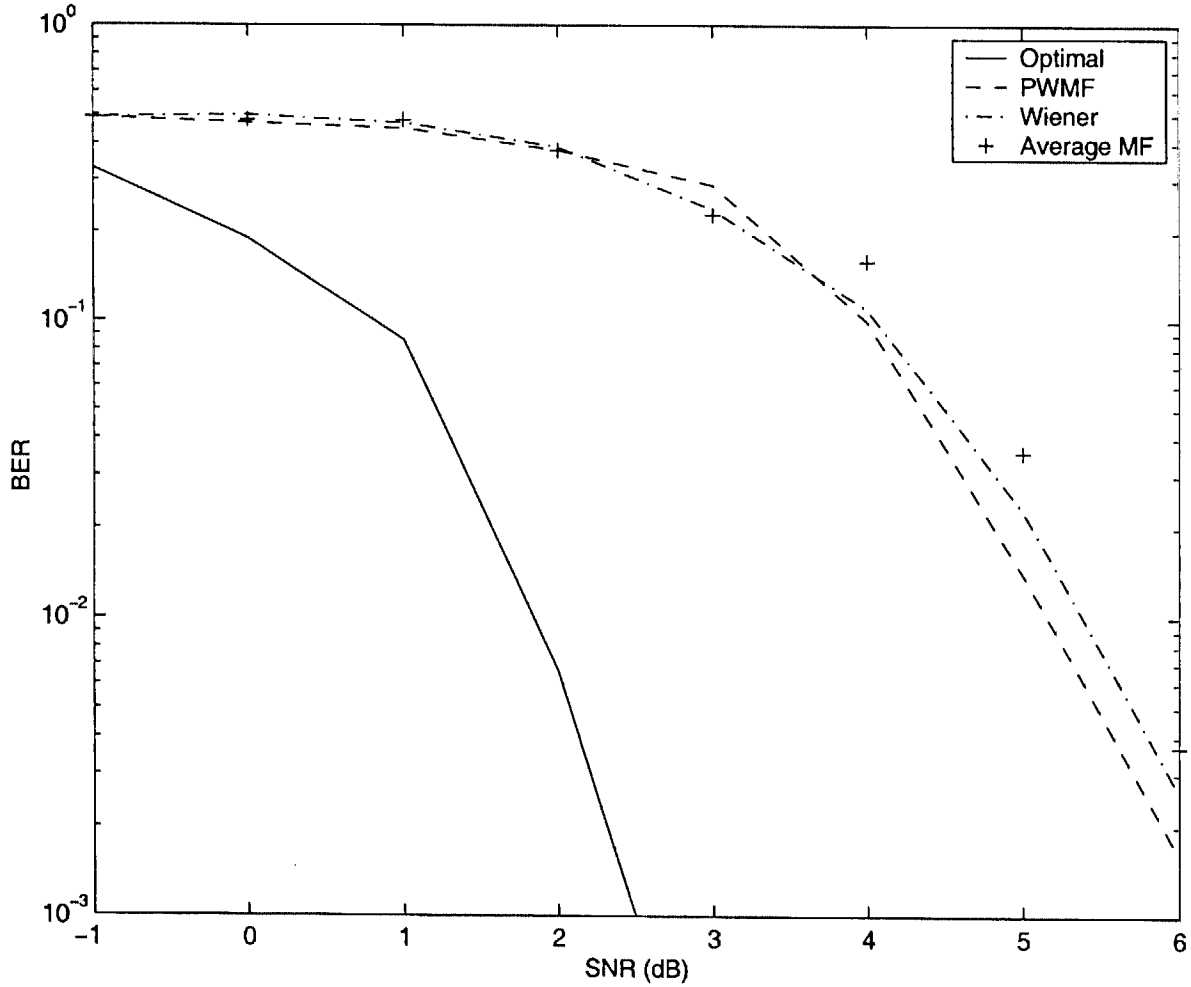
BER Analysis/Simulation for uncoded EFQPSK



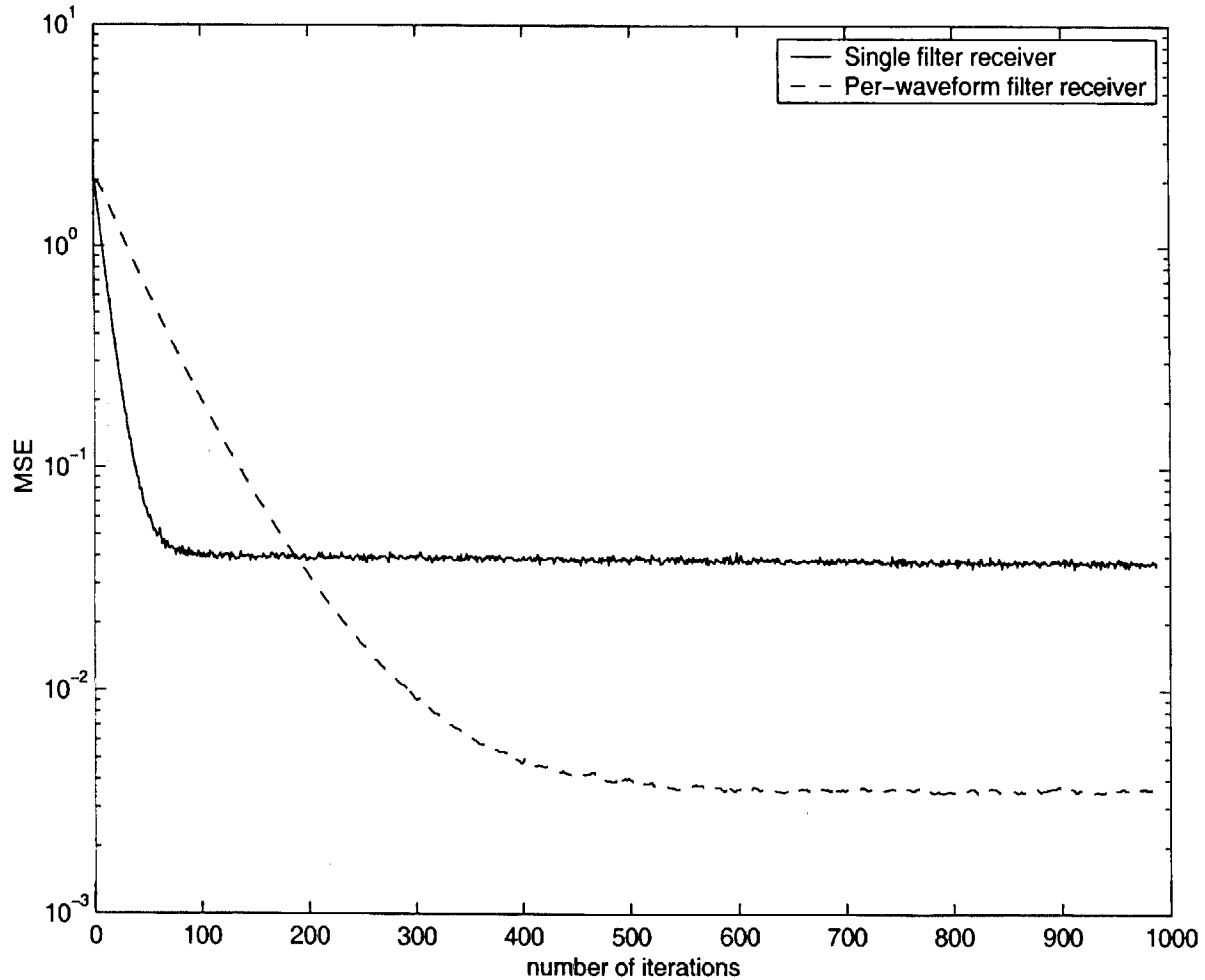
Sensitivity to predistorter phase error (EFQPSK)



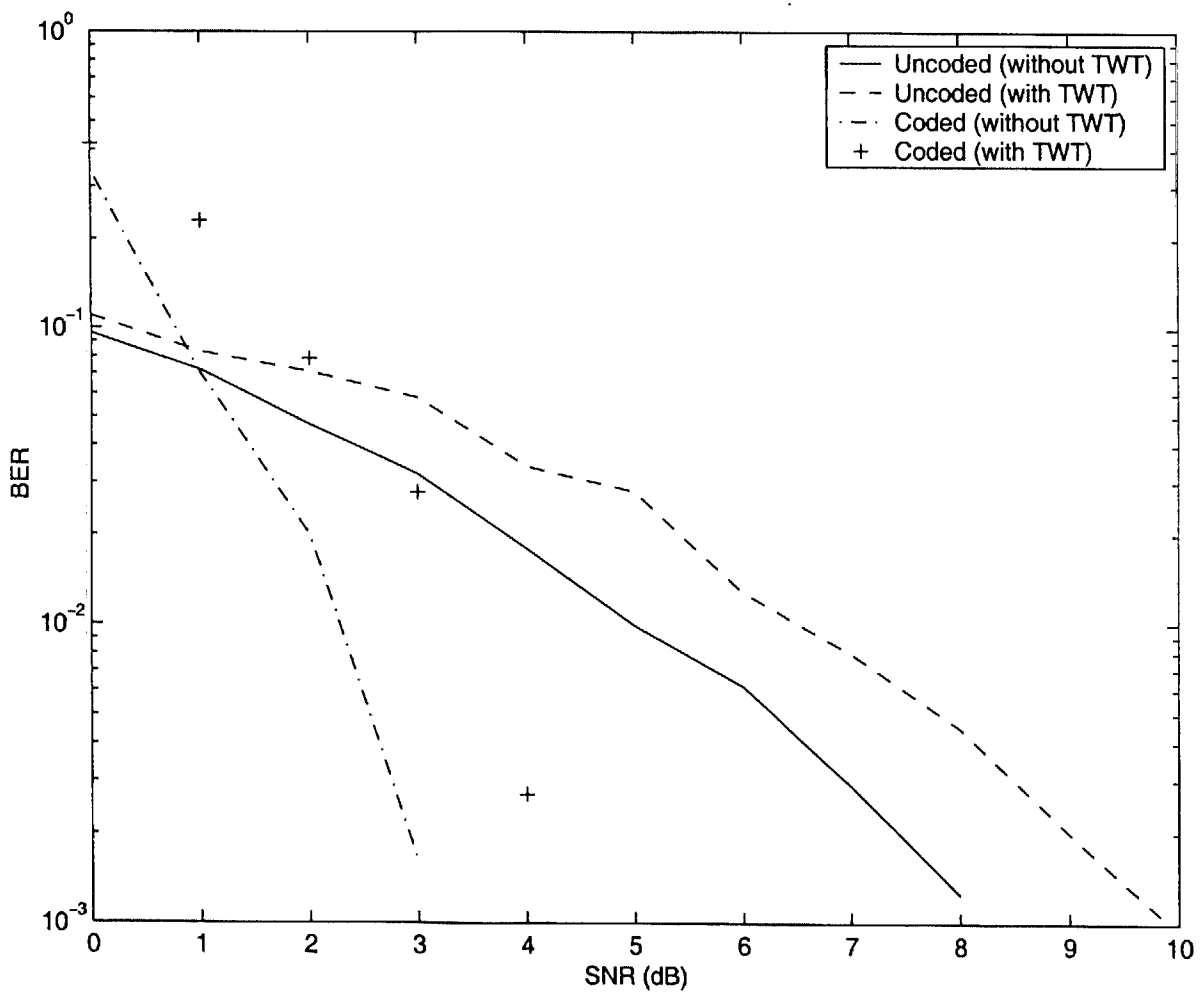
BER Performance of Coded EFQPSK)



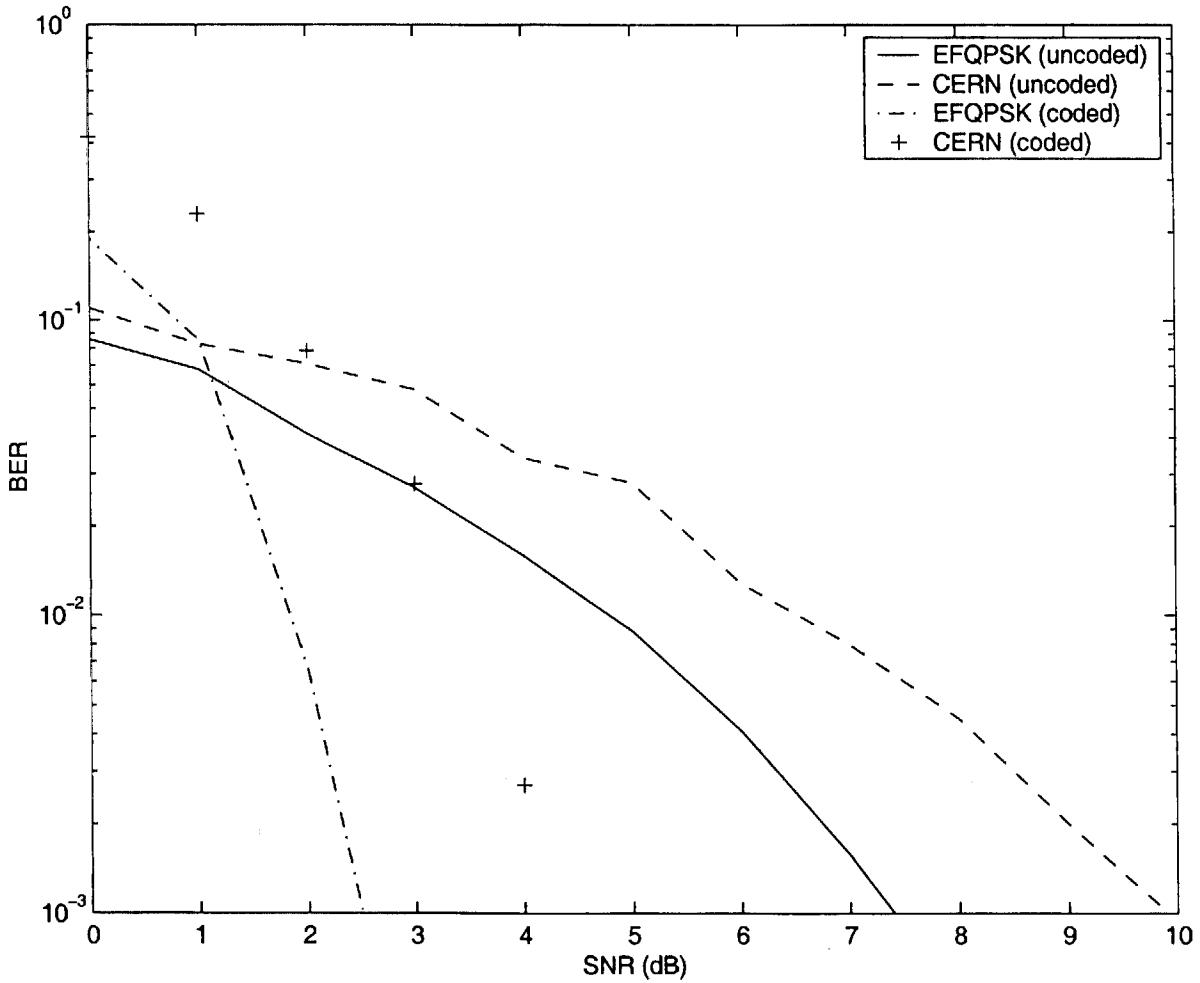
Convergence of Adaptive Receivers for EFQPSK)



BER Performance of QPSK CERN



BER Performance Comparison (TWT:0 dB IBO)



BER Performance of EFQPSK and CERN

- Several receiver structures are available for EFQPSK providing complexity performance trade off.
- BER performance of EFQPSK is negligibly affected by the nonlinear amplifier.
- BER performance of CERN is degraded by more than 1 dB due to the nonlinear amplifier.
- Ignoring other features of the modulation techniques, the EFQPSK is found to provide more than 2 dB performance improvement over CERN.

Possible Future Directions

- Improvement on EFQPSK to suppress the spectral lines for unbalanced data.
- Improvement on CERN technique.
- Adaptive predistorter investigation and realization with improved CERN.
- Efficient detection in intersymbol interference environment.

Conclusions

- A comparative study on EFQPSK and CERN techniques is considered and both the techniques are found to have advantages and disadvantages.
- The CERN method is found to have better bandwidth efficiencies, especially when higher modulation formats are used.
- The CERN requires good adaptive predistorter to fully utilize its potential spectral benefits.
- The EFQPSK provides better power efficiencies than CERN.
- Several future research directions in terms of improving the performance of EFQPSK and CERN techniques have been indicated.

Bandwidth-efficient Transmission in Nonlinear Satellite Channels

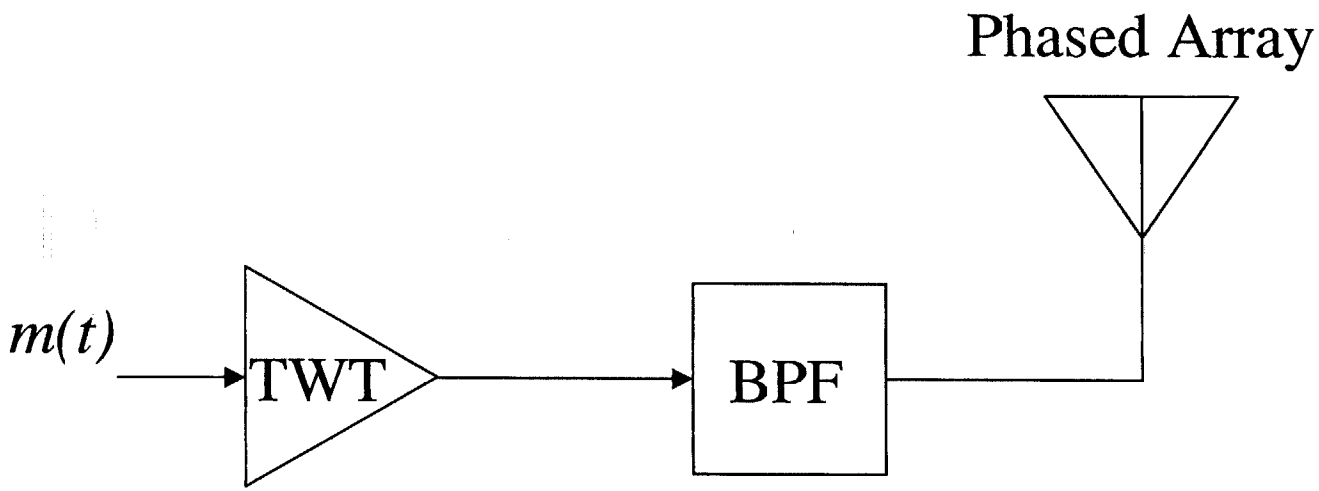
Raphael J. Lyman

New Mexico State University

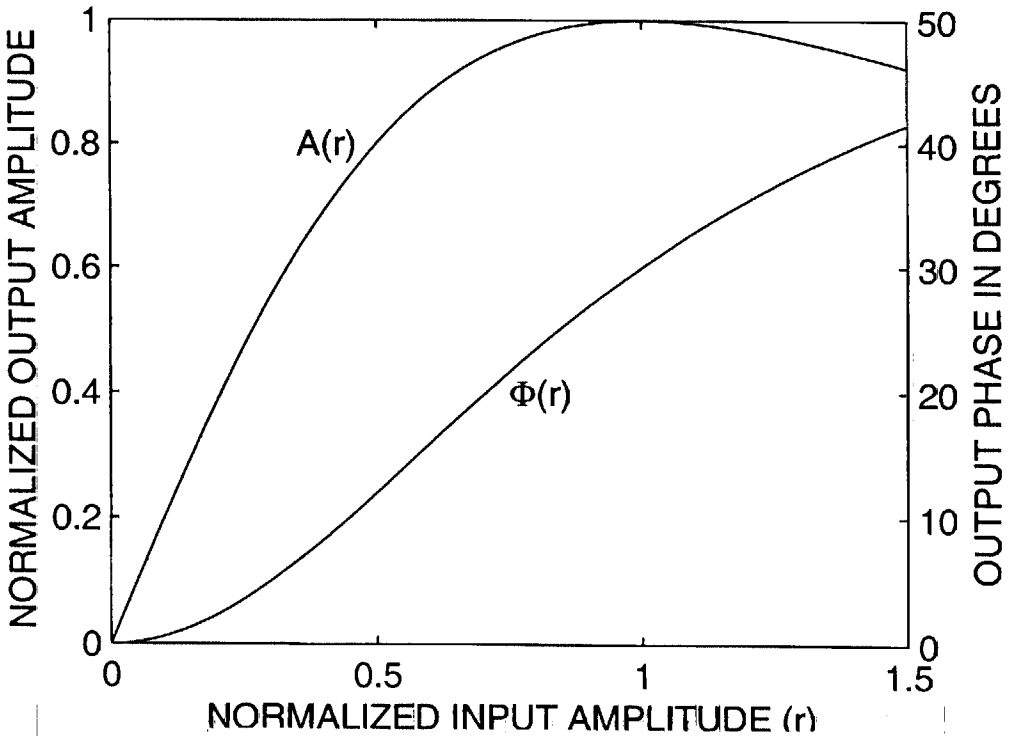
Personal Background

- Graduated University of Florida, May 2000
- Dissertation: Linear Prediction of Bandlimited Processes
- Research interests:
  - Channel modeling
  - Estimation theory
  - Wireless communications

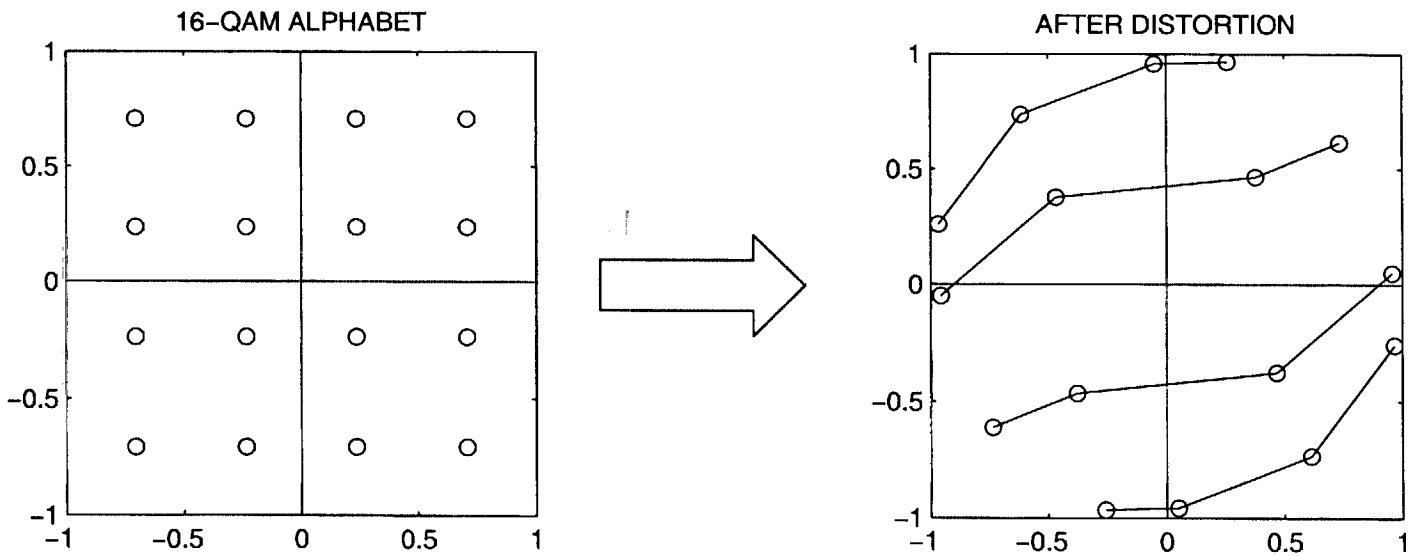
Satellite Channel Model



TWT Characteristic

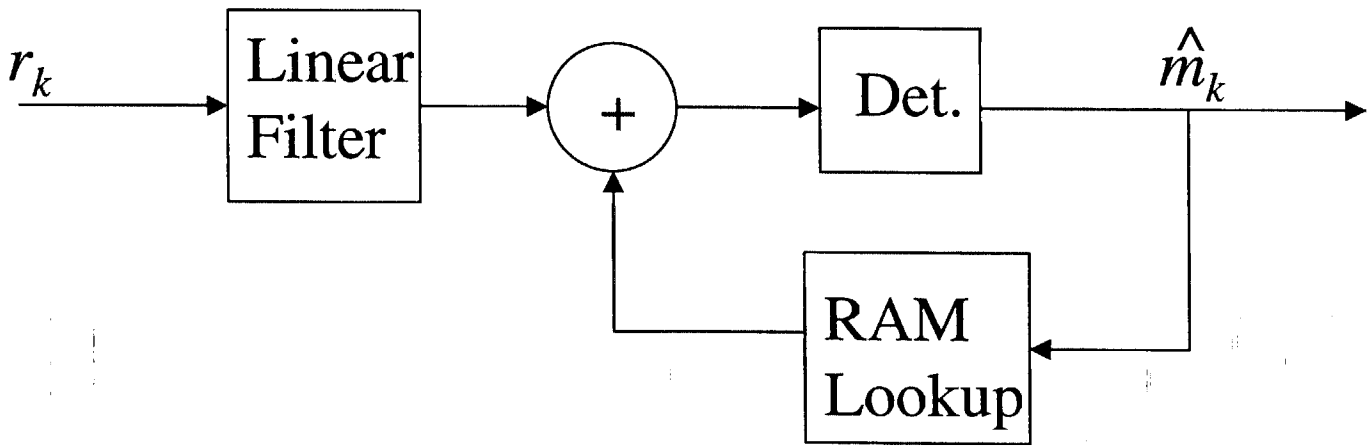


Distortion of QAM Alphabet



Proposed Solutions

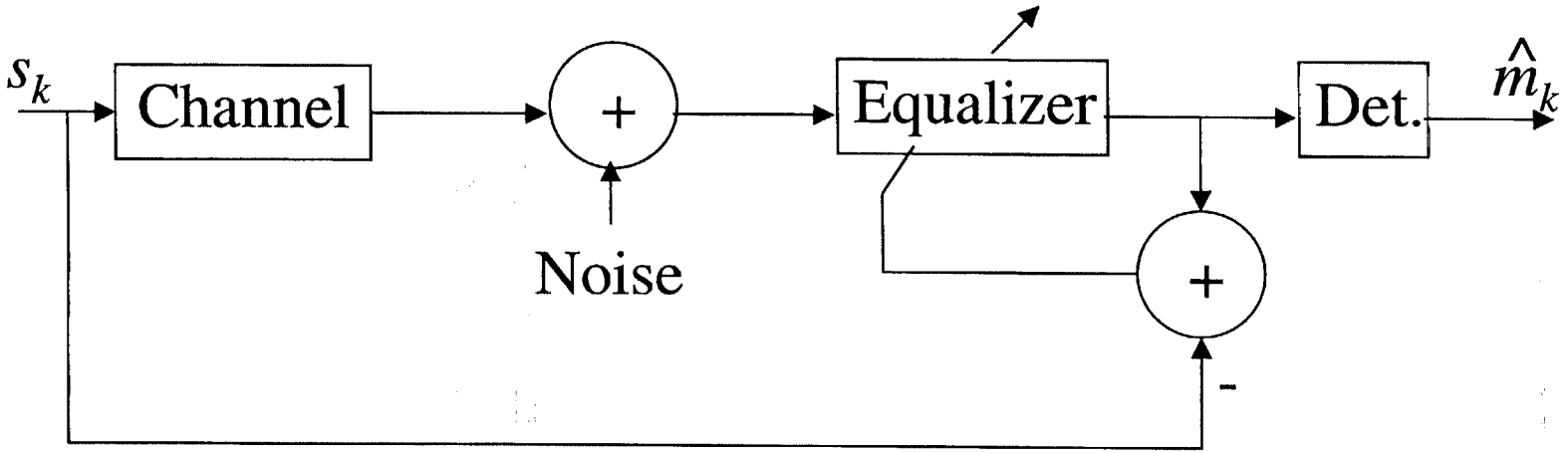
- Adaptive predistortion (demod on TX)
- Volterra filters (noise sensitivity?)
- RAM DFE (training time)



My Focus

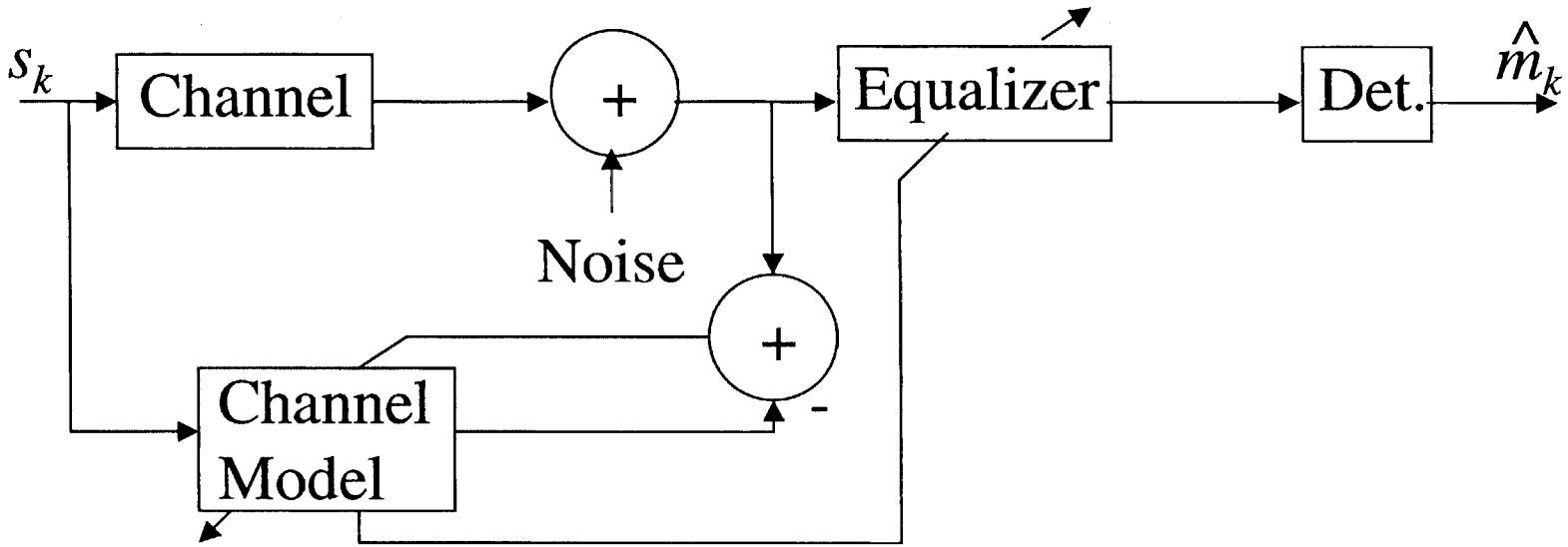
- Channel modeling
  - Nonlinear memoryless cascaded with linear ISI
  - Very slow variation of nonlinear characteristic
- Channel estimation
  - Faster convergence than direct adaptation
  - Run TWT in linear region during adaptation

Direct Adaptation



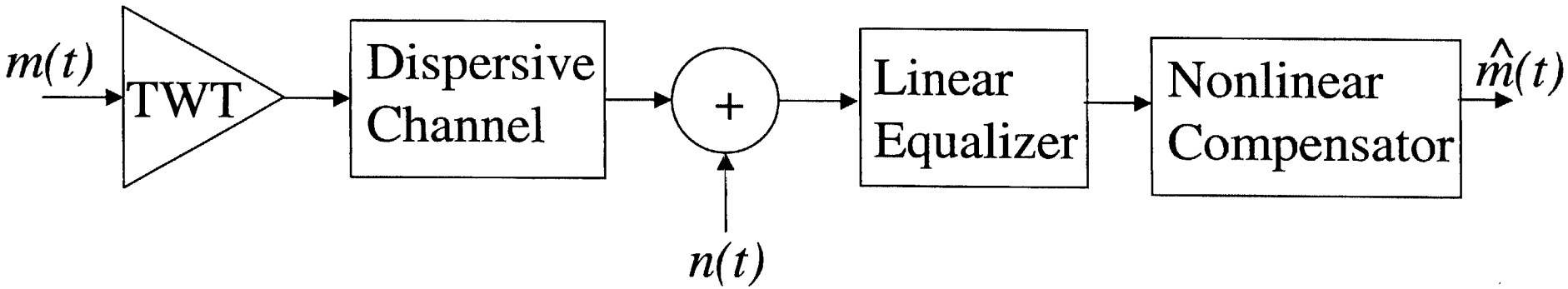
- Equalizer parameters updated directly
- LMS or RLS commonly used algorithms

Indirect Adaptation



LMS and RLS performance nearly identical.

Channel Modeling

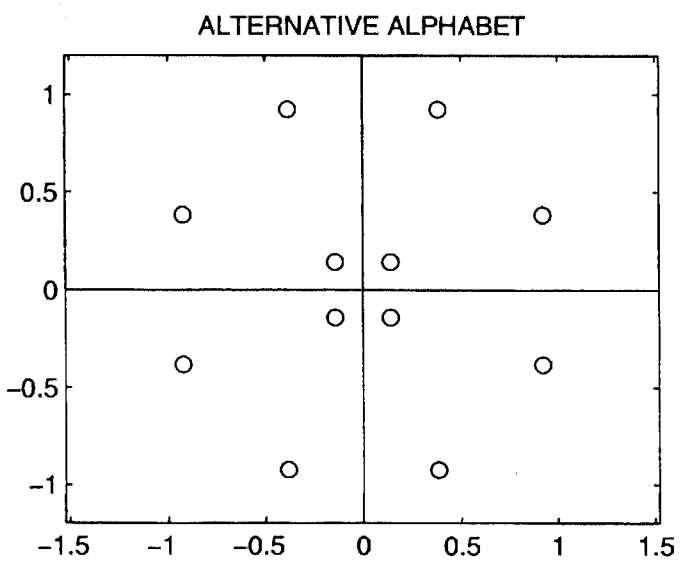


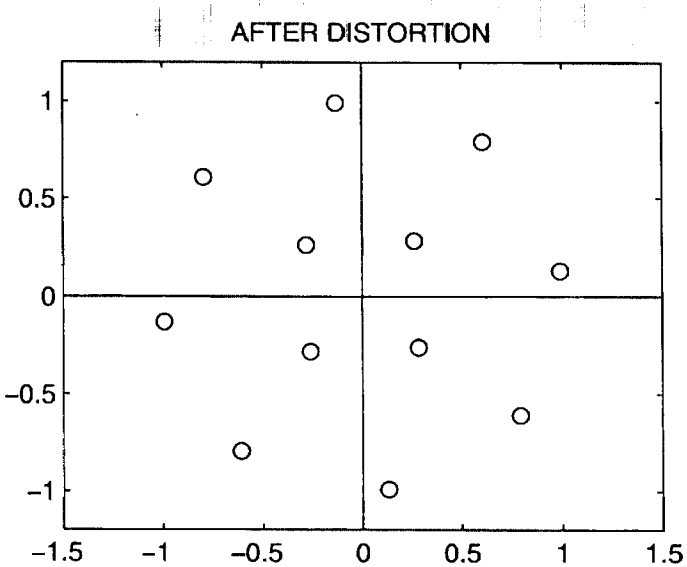
- What about the noise?
- Avoid overly general compensation techniques.
- Use adaptation to get you "the last cm".

> Keep it as simple as possible, not simpler.

Examples

- Nonadaptive predistortion
- Ring-type QAM alphabet





Action Items

- Refine channel models.
  - Nonlinearities and dispersion separable?
  - Which elements slowly varying?
  - Can channel types be usefully classified?
- Review proposed compensation techniques.
- Develop or borrow simulation software.

Conclusions

- General approaches are not always general solutions.
- Nonlinear channels may require more case-by-case consideration.
- Choose solutions that fit the particular channel model.
- First step is good channel modeling and estimation procedures.

Lightweight Optical Wavelength Communications a Laser in Space

by
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Las Cruces, NM

CURRENT SPONSORS

- NASA
- New Mexico Space Grant Consortium

LOWCAL vs. RF

LOWCAL Goals

- Data Rate: 10 kbps
- Lightweight: < 2 pound
- Ultra low power consumption: < 500mW
- Day / night operation
- LEO communication without a laser in space

RF Communication

- Data Rate: 10 kbps
- Weight: ~ 10 pounds (heat sink weight)
- Power consumption: ~ 10W

LOWCAL LINKS

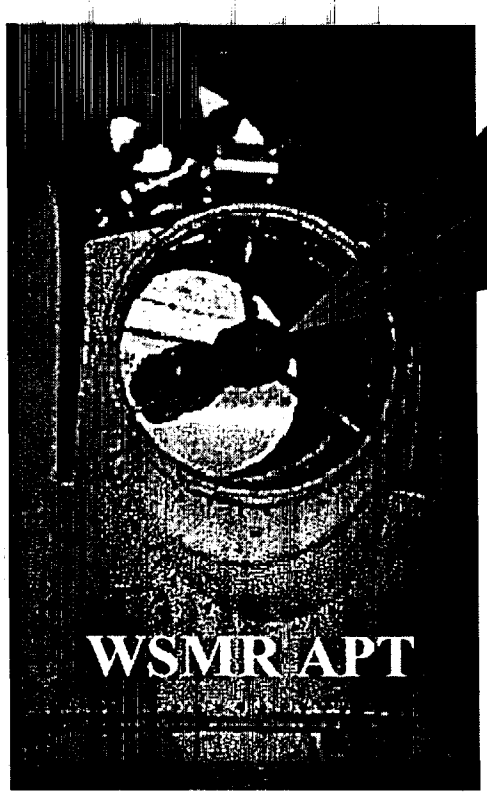
852-nm uplink
downlink carrier

852-nm downlink

signal beam

LOWCAL: Lightweight Optical Wavelength Communication without A Laser in space

Satellite Acquisition



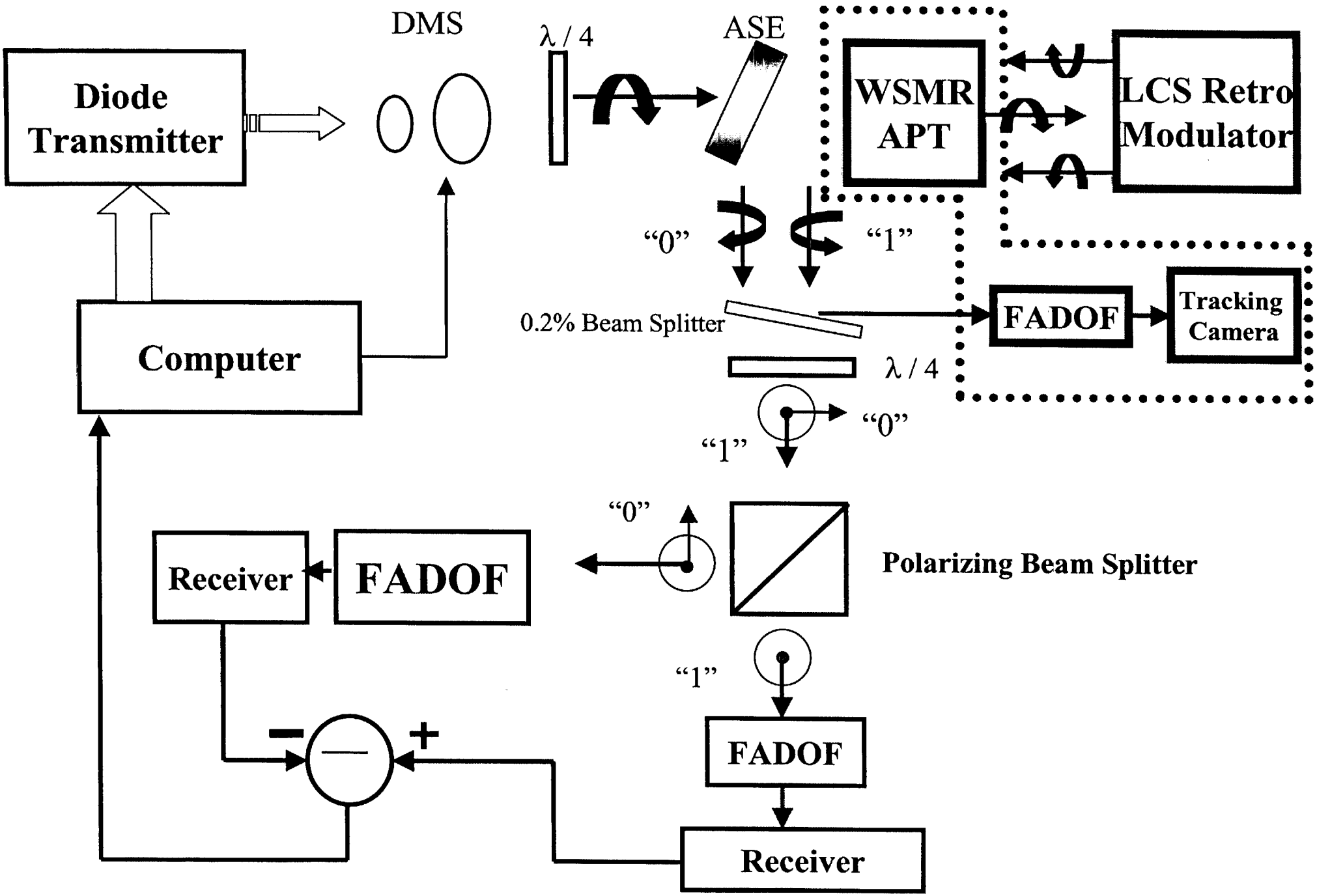
In-Space Spot Size:
Acquire: ~100m
Locked: 7 m

Comparison With Other Experiments

	LOWCAL	AF/PL/USU
Platform	Space Shuttle	Balloon
Range	640 km	32 km
Data Rate	10 kbps	1.2 kbps
Telescope Diameter	0.6 m	1.5 m
Modulator Weight	2-4 kg	28 kg
Retro-Modulator Area	70-180 cm^2	1-10 cm^2
24 Hour Capability?	Yes	No
Transmitter Power	0.2 W	5 W

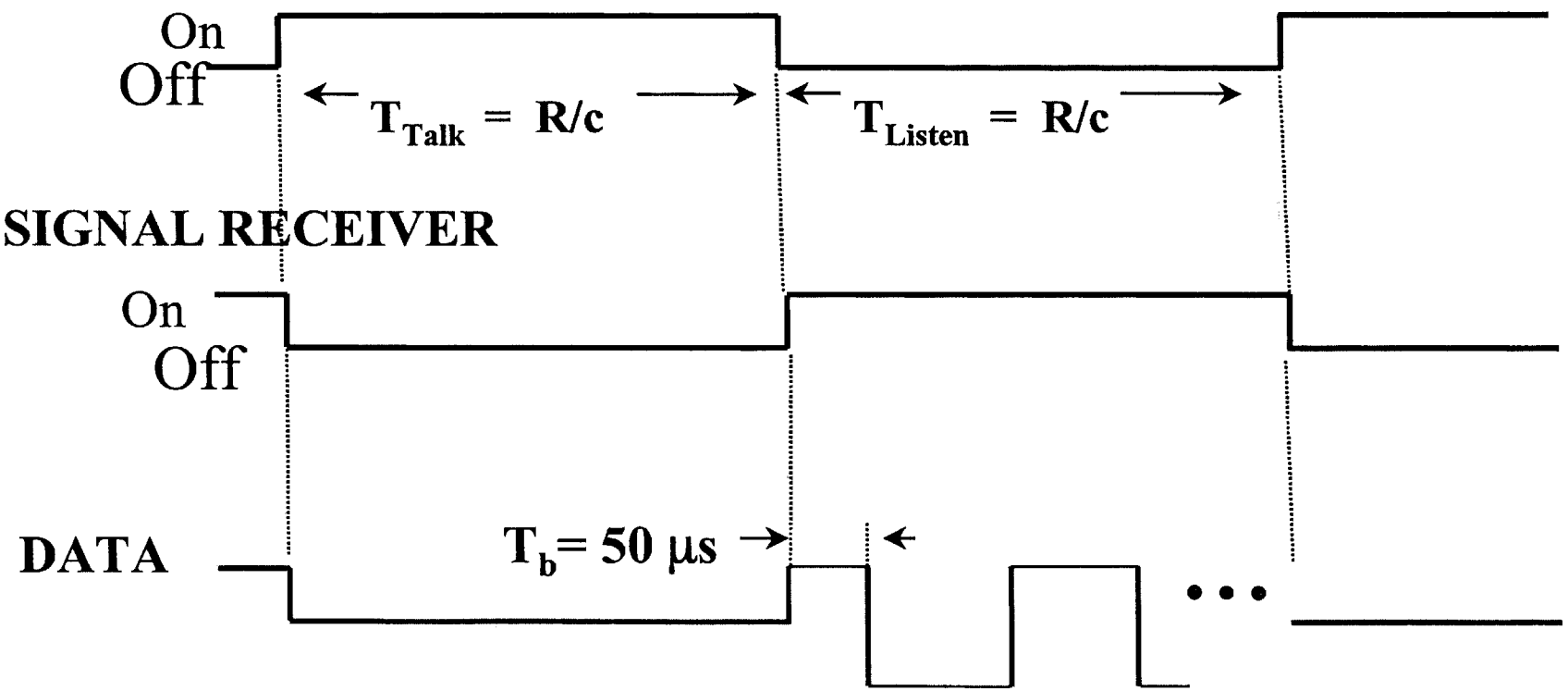
DOWNLINK SECTION

LOWCAL with Differential Circular Polarization Keying



DCPK COMMUNICATIONS FORMAT

CARRIER TRANSMISSION



where c represents the speed of light

DOWNLINK LINK EQUATION

$$P_s(dB) = P_T(dB) - 2\,L_T - 2\,L_{Atm} - L_{mod} - L_{CIE} - L_{SIE}$$

where:

$$L_T = -10\log(\eta_T) \qquad L_{Atm} = -10\log(T_{Atm})$$

$$L_{FADOF} = -10\log(T_{FADOF}) \qquad L_{mod} = -10\log(\eta_{mod}^2\,\eta_{retro})$$

$$L_{CIE} = -10\cdot\log\left(\frac{A_{retro}}{R^2\cdot\Delta\Omega_{up}}\right) \qquad L_{SIE} = -10\cdot\log\left(\frac{A_r}{R^2\cdot\Delta\Omega_{down}}\right)$$

$$Margin = P_T - 2\,L_T - 2\,L_{Atm} - L_{mod} - L_{CIE} - L_{SIE} - P_{min} - M_{scintillation}$$

where:

$M_{scintillation}$ **represents the margin required to compensate for beam scintillation.**

APPROXIMATE SIGNAL

Taking into account dependence of Zenith angle, ϕ, on the effective retro-modulator area and range to the spacecraft we obtain,

$$P_s = P_T \cdot \eta_T^2 \cdot \eta_{\text{mod}}^2 \cdot \eta_{retro} \cdot T_{Atm}^2 \cdot T_{FADOF} \cdot \frac{A_r \cdot D_{retro}^4 \cdot \cos^4(\phi) \cdot \cos^2(\phi - \alpha)}{H_{orbit}^4 \cdot \pi \cdot (1.22 \cdot \lambda)^2 \cdot \theta_{Trans}^2}$$

Where:

D_{retro} represents the retro-modulator diameter

ϕ represents the spacecrafts angle with Zenith

DCPK SNR

$$SNR = \frac{\left(2 \cdot P_s \cdot (1-\varepsilon) \cdot R_{PD}\right)^2}{\left[2 \cdot q \cdot B \cdot \left(P_s \cdot (1-2\varepsilon) \cdot R_{PD} + I_D\right) + \left(\frac{4 \cdot k \cdot T \cdot B \cdot F_t}{R_L}\right)\right]}$$

Where:

q represents the electron charge.

B represents the signal bandwidth.

R_{PD} represents the photodetector responsivity.

I_D represents the photodetectors dark current.

k represents Boltzmans constant.

T represents the temperature in degrees Kelvin.

R_L represents the load resistor.

F_t represents the noise figure of the amplifier.

ε represents the extinction ratio of the LCS

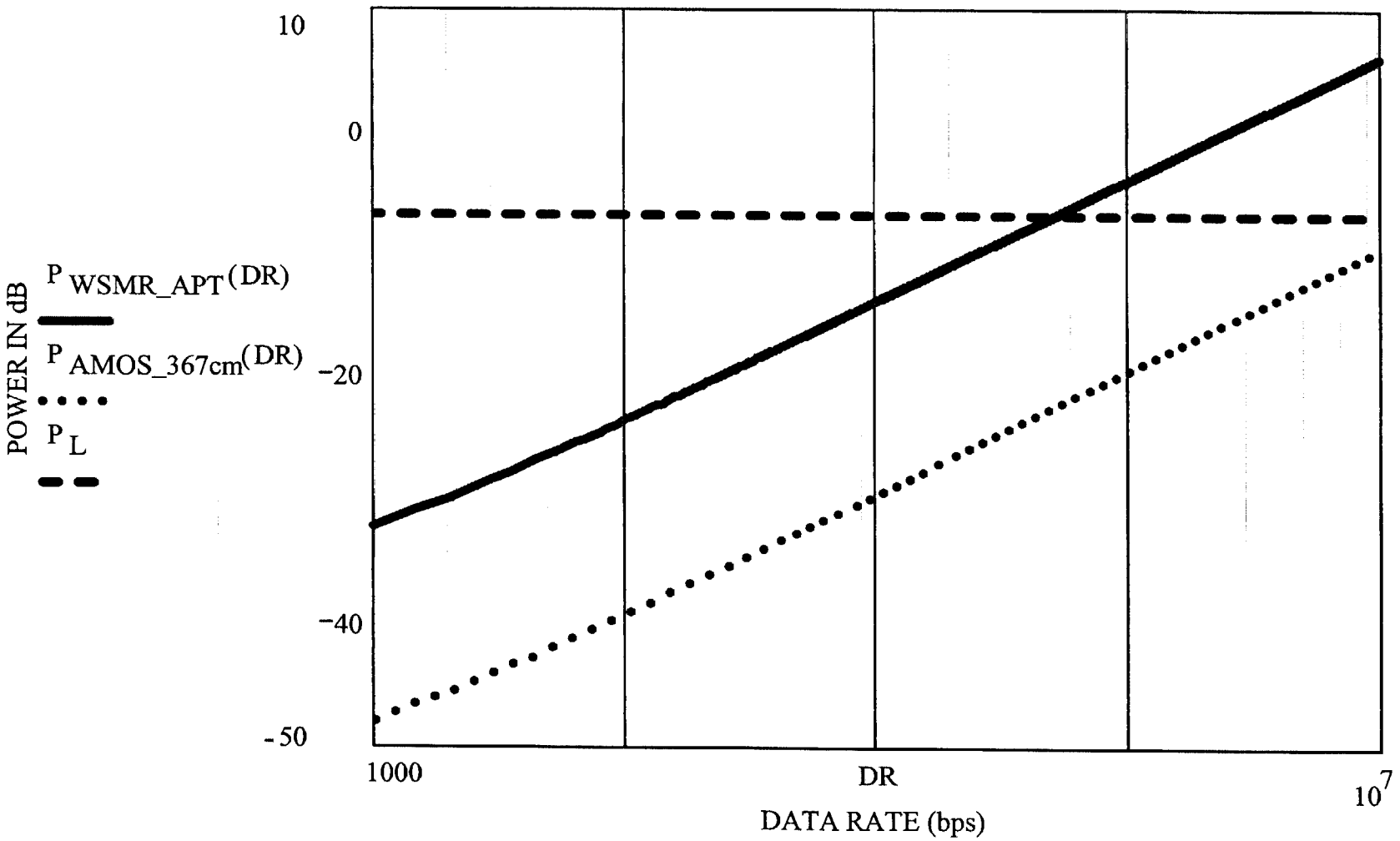
DCPK-SNR

In our case shot noise dominates, thus the SNR reduces to,

$$SNR = \frac{2 \cdot P_s \cdot \eta_{PMT} \cdot q}{2 \cdot q \cdot B \cdot h \cdot \nu} = \frac{P_s \cdot \eta_{PMT}}{B \cdot h\nu}$$

$$SNR = P_T \cdot \eta_T^2 \cdot \eta_{\mathrm{mod}}^2 \cdot \eta_{retro} \cdot T_{Atm}^2 \cdot T_{FADOF} \cdot \frac{A_r \cdot D_{retro}^4 \cdot \cos^4(\phi) \cdot \cos^2(\phi - \alpha)}{H_{orbit}^4 \cdot \pi \cdot (1.22 \cdot \lambda)^2 \cdot \theta_{Trans}^2} \frac{\eta_{PMT}}{B \cdot h\nu}$$

DATA RATE VERSUS POWER



Maximum angle from Zenith 60 degrees

SYSTEM CHARACTERISTICS

Transmitter power	-7 dB
Receiver diameter	60 cm
Maximum data rate	10 kb/s
Acquisition integration time	0.01 sec.
$M_{scintillation}$	10-dB

Losses

Description	Loss (dB)
Modulator	1.4
Atmospheric	2*3
Telescope	2*0.5
FADOF	1
Carrier Intercept at Spacecraft	46
Signal Collection at the ground	24
Total	79.4

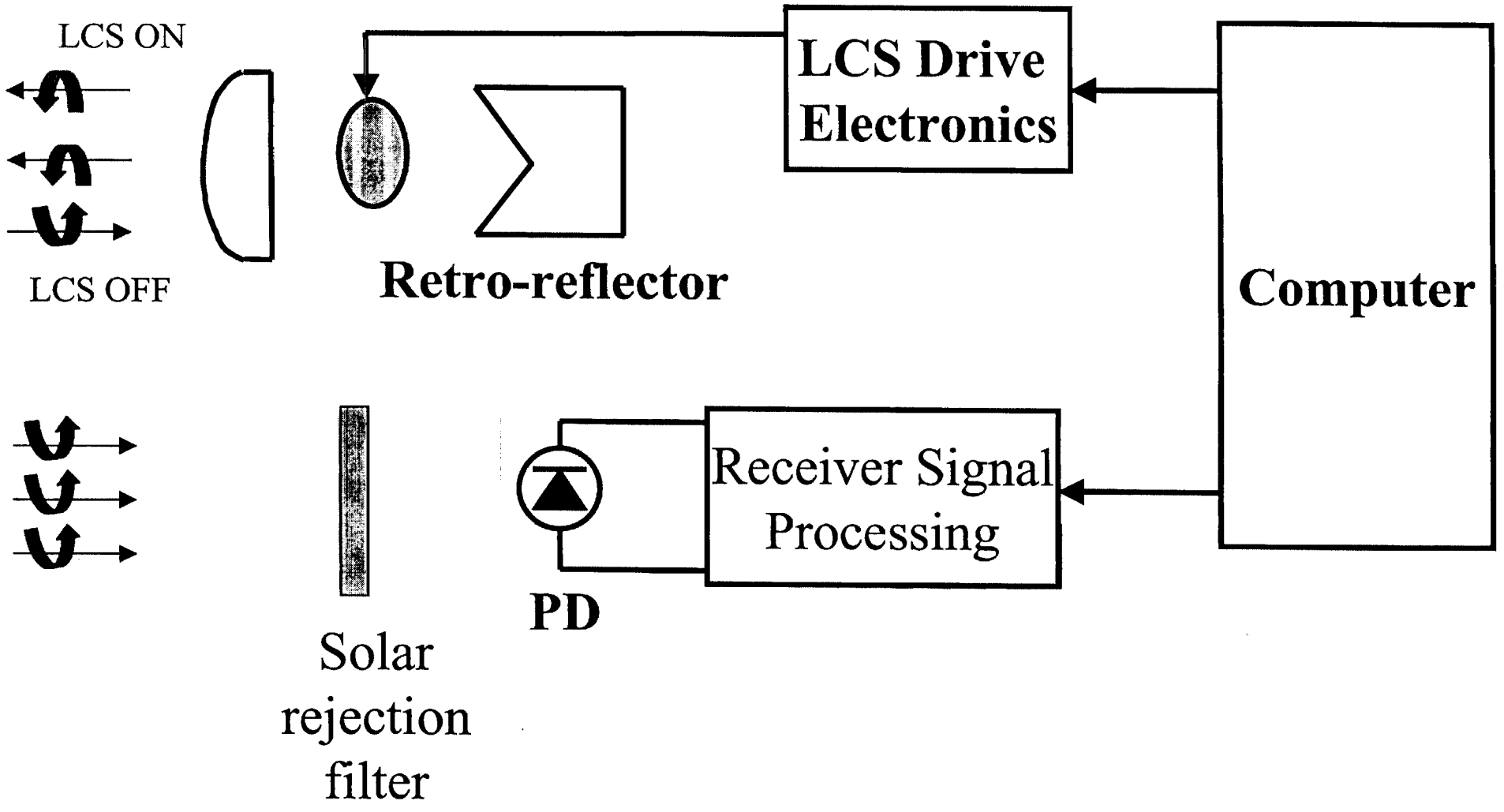
Link margin **20-dB**

DOWNLINK SUMMARY

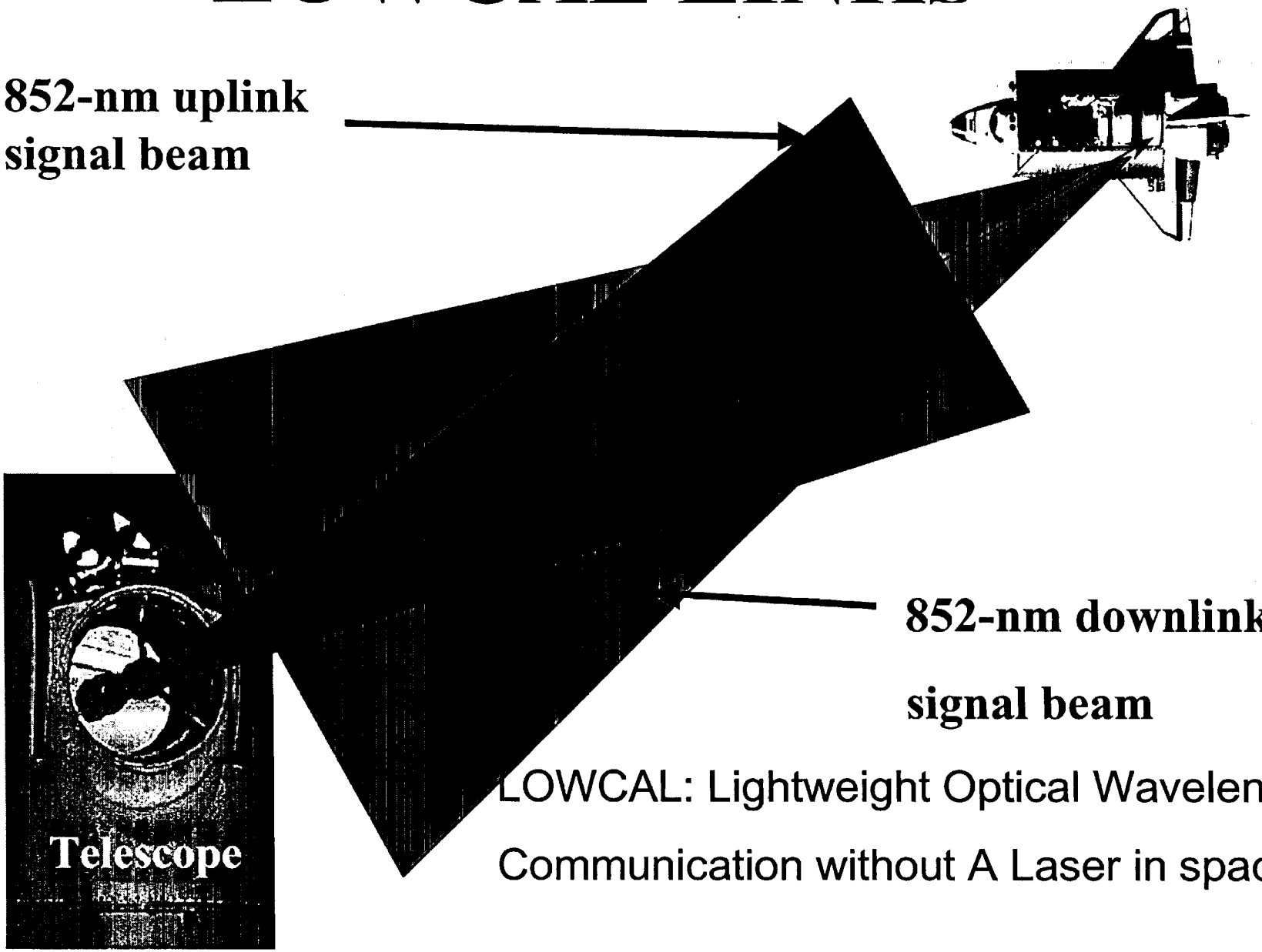
- 10 kbps Data rate planned to LEO with a 20 dB margin
- First Circular Polarization Keying concept. (patent pending)
  - DCPK provides 6 dB SNR increase.
- 24 hour a day operation.
- Lightweight and low power consumption in space.
- With faster modulators data rates of Mb/s are possible

UPLINK SECTION

LIGHTWIRE FLIGHT SUBSYSTEMS

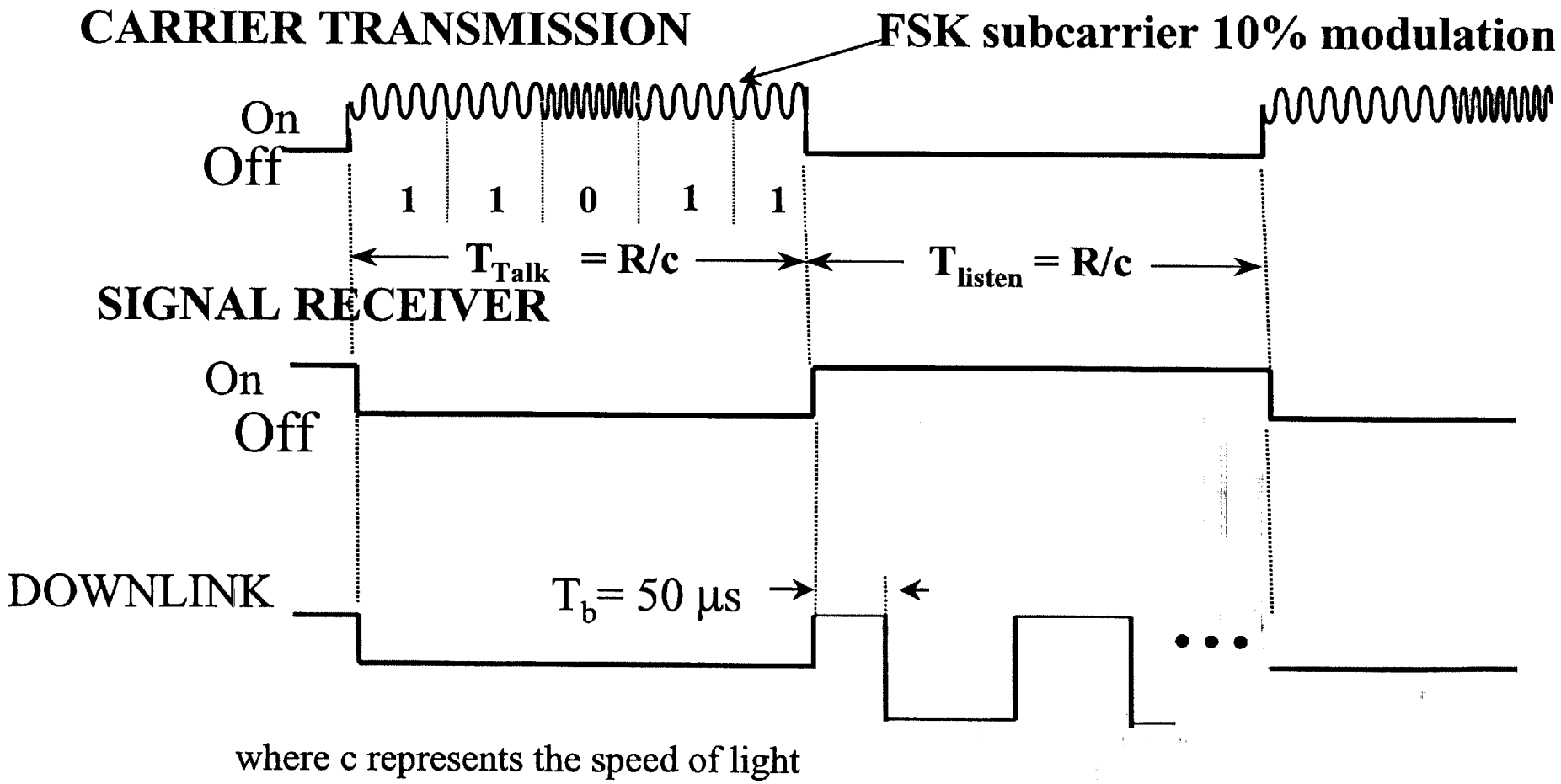


LOWCAL LINKS



LOWCAL: Lightweight Optical Wavelength Communication without A Laser in space

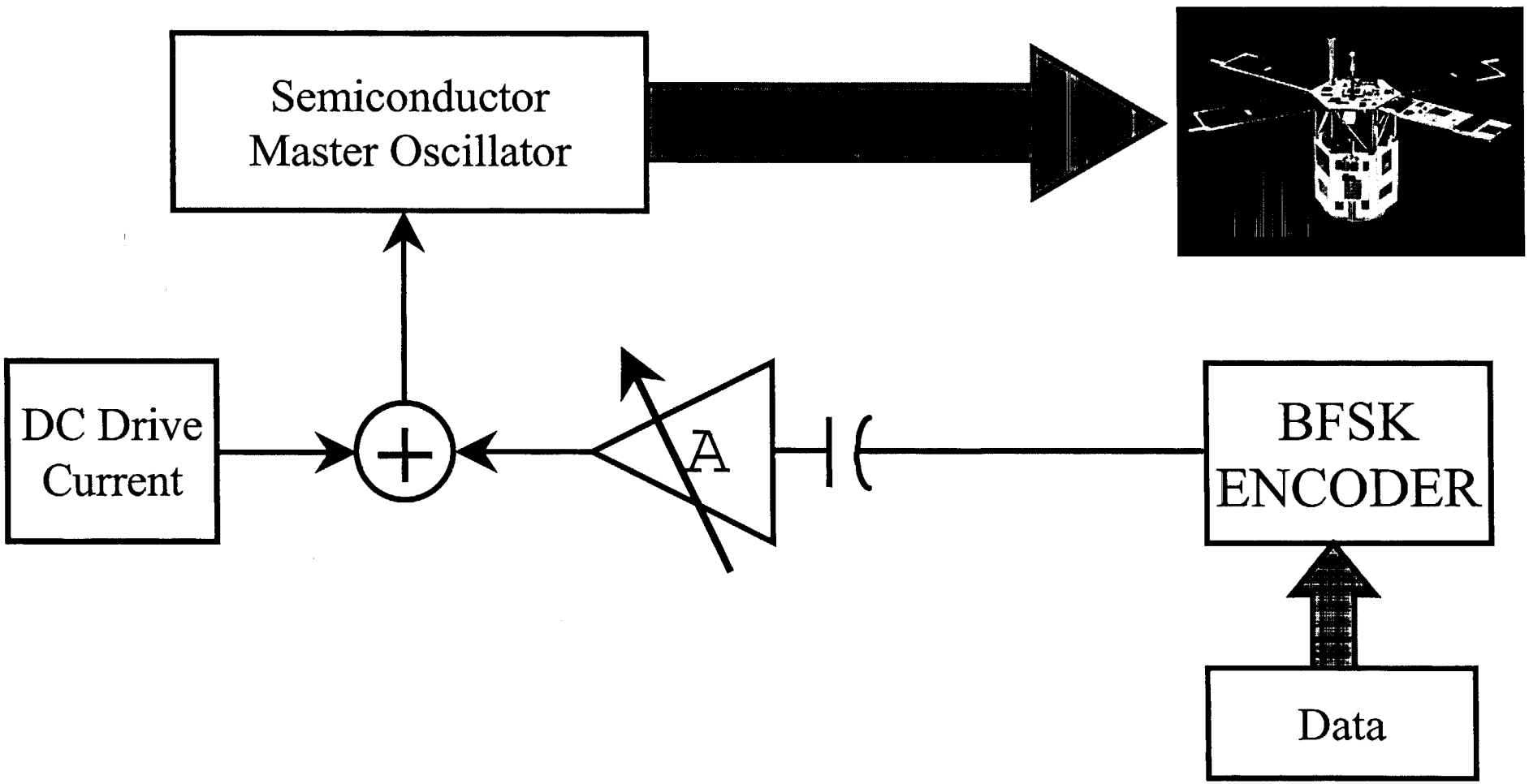
LIGHTWIRE FORMAT



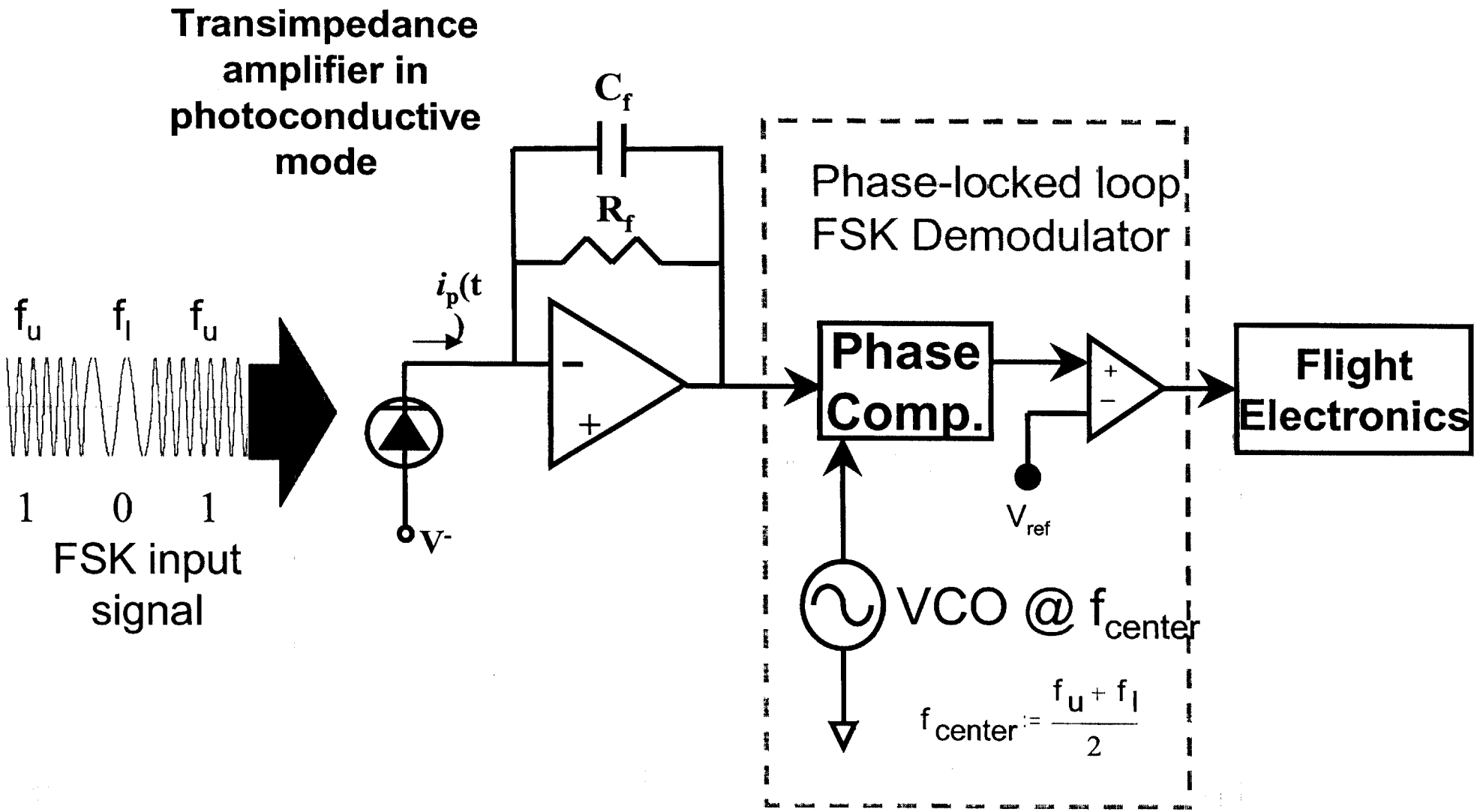
where c represents the speed of light

Conceptual Block Diagram for Uplink Modulation

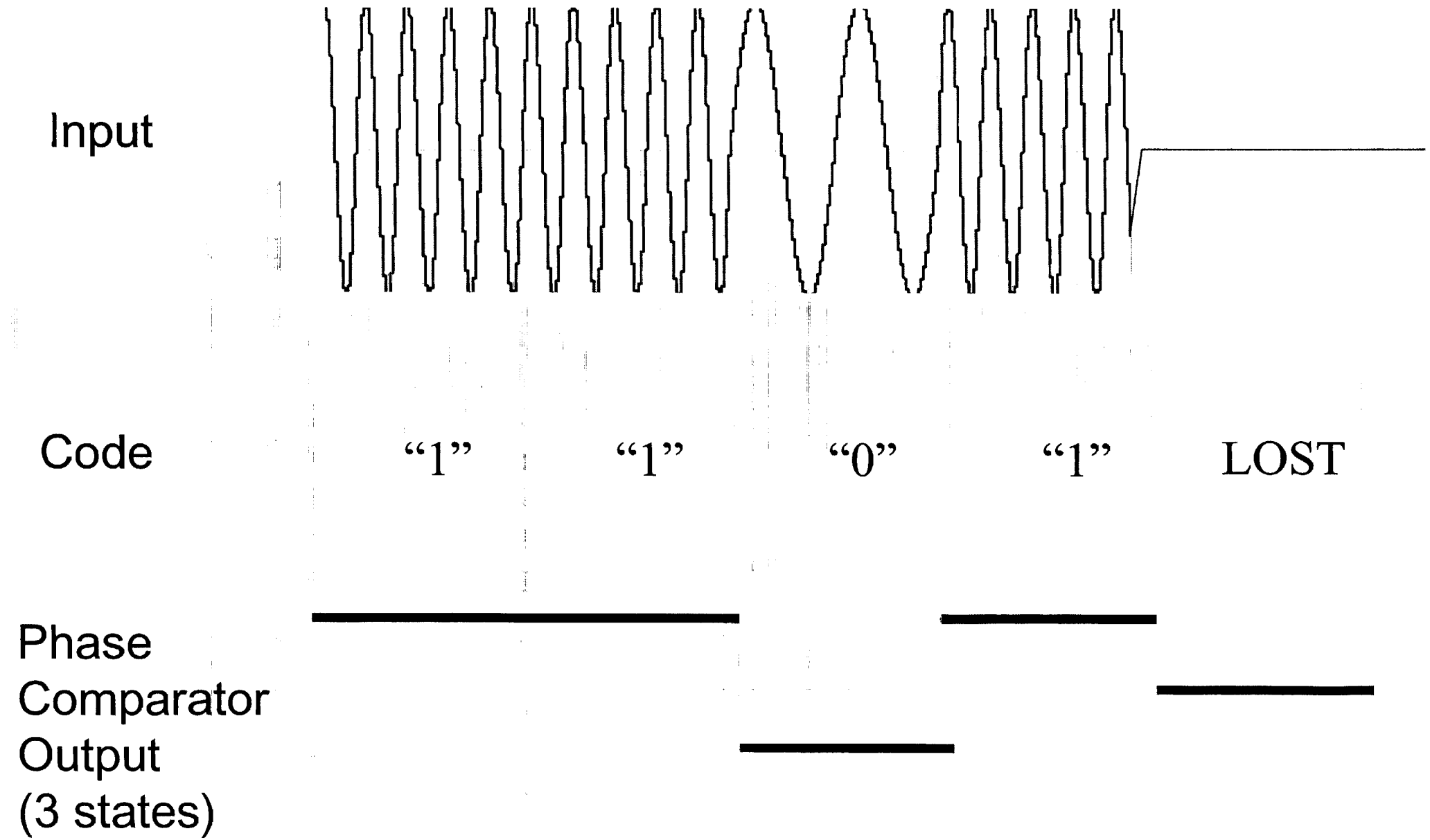
$P_{mo} \bullet (1 + 0.1) \cos(\omega_{fsk} t))$



Lightwire FSK Demodulation



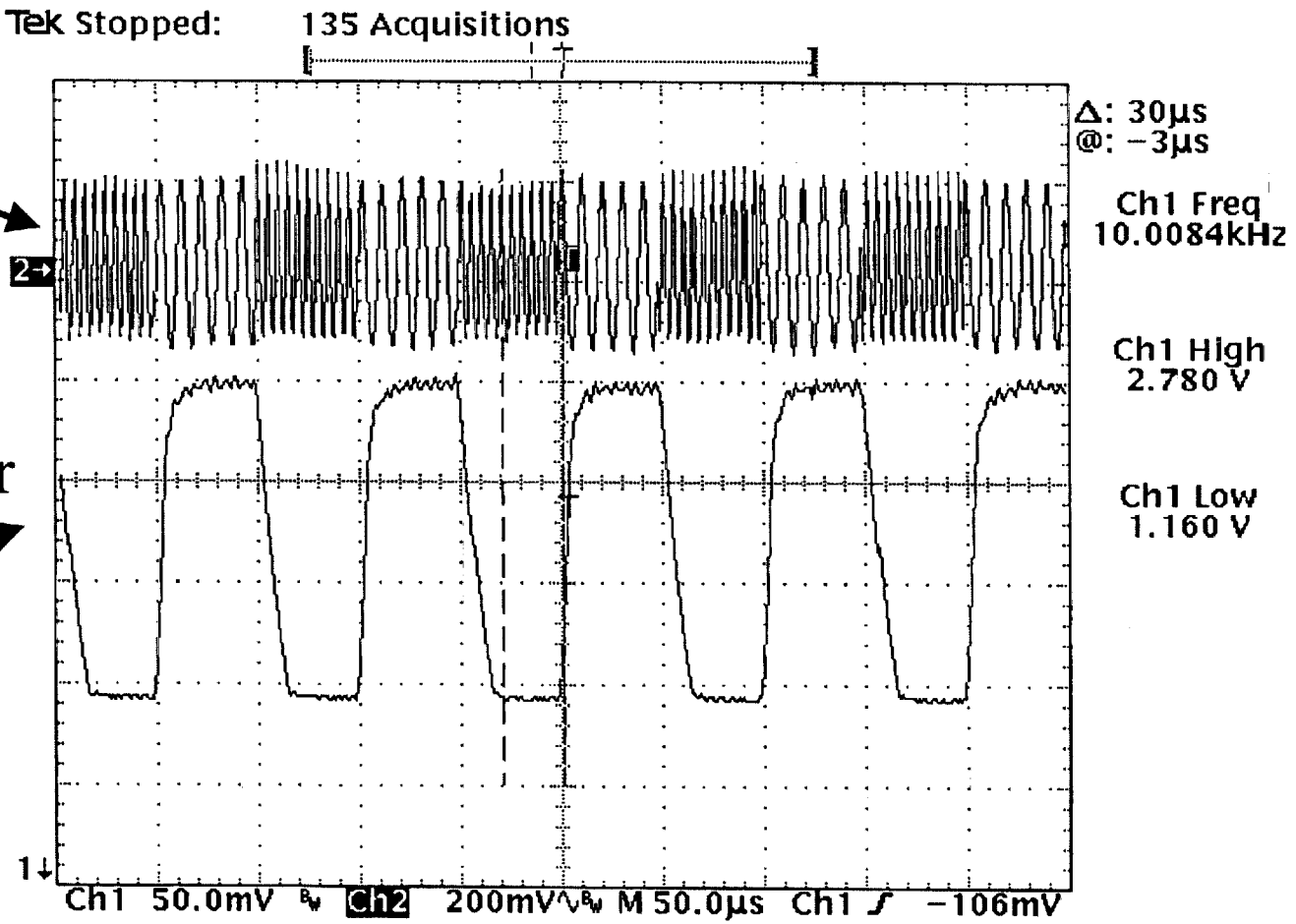
FSK Demodulation Theoretical



FSK Demodulation Experimental

FSK Input Signal

FSK Demodulator Output



UPLINK SIGNAL

The optical power incident upon the spacecraft P_r is,

$$\mathbf{P_r = I_i A_{PD} [1 + m \cos(\omega_{FSK} t)]}$$

where:
P_r represents the received optical power at the spacecraft.
I_i represents the intensity incident upon the spacecraft.
m represents the modulation index.
ω_{FSK} represents the subcarrier frequency.

UPLINK SNR CALCULATIONS

$$SNR = \frac{\frac{1}{2} \cdot (m \cdot P_r \cdot R_{PD})^2}{\left(2 \cdot q \cdot B \cdot (P_r \cdot R_{PD} + I_D) + \frac{4 \cdot k \cdot T \cdot B}{R_L} \cdot F_t \right)}$$

Where:

q represents the electron charge.

B represents the signal bandwidth.

R_{PD} represents the photodetector responsivity.

I_D represents the photodectors dark current.

RIN represents the laser relative intensity noise.

k represents Boltzmans constant.

T represents the temperature in degrees Kelvin.

R_L represents the load resistor.

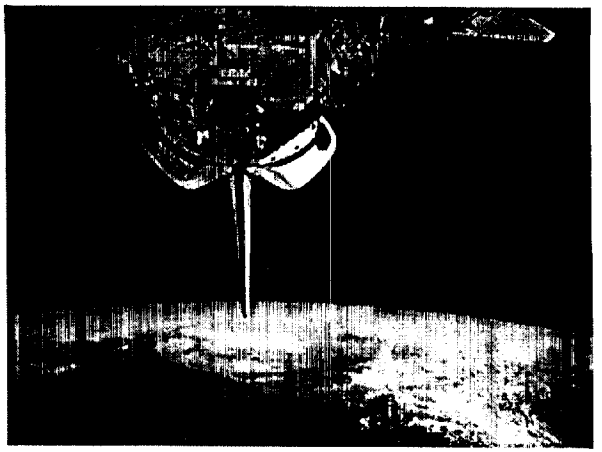
F_t represents the noise figure of the amplifier.

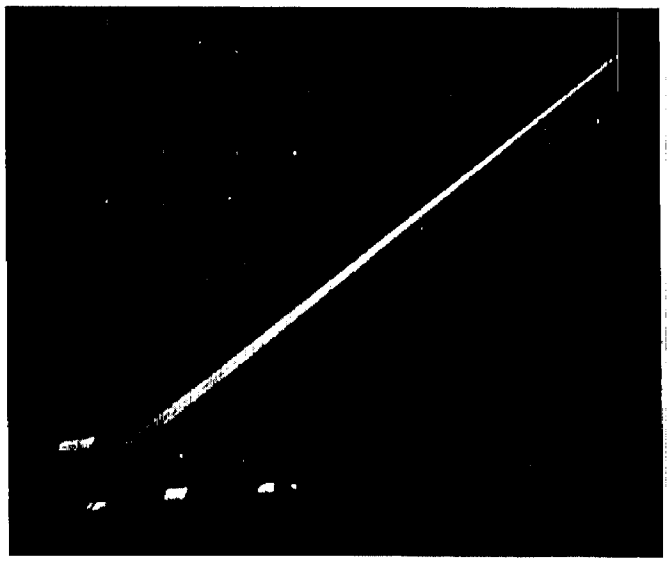
PRELIMINARY UPLINK MODEL RESULTS

Incident Intensity	**50 nW/cm^2**
Eye Safety limit	**2 mW/cm^2**
Photodetector area	**4.0 cm^2**
Photodetector responsivity	**0.6 amp/watt**
modulation index	**0.1**
Data Rate	**10 kHz.**
Load resistance	**25 kohm**
FSK Signal to Noise	**36 dB**
FSK signal current	**89 nA**

Summary of Unique Features

- Sunlight insensitive operation
- No laser in space
- All pointing is on the ground
- Very low power consumption
- Very low mass



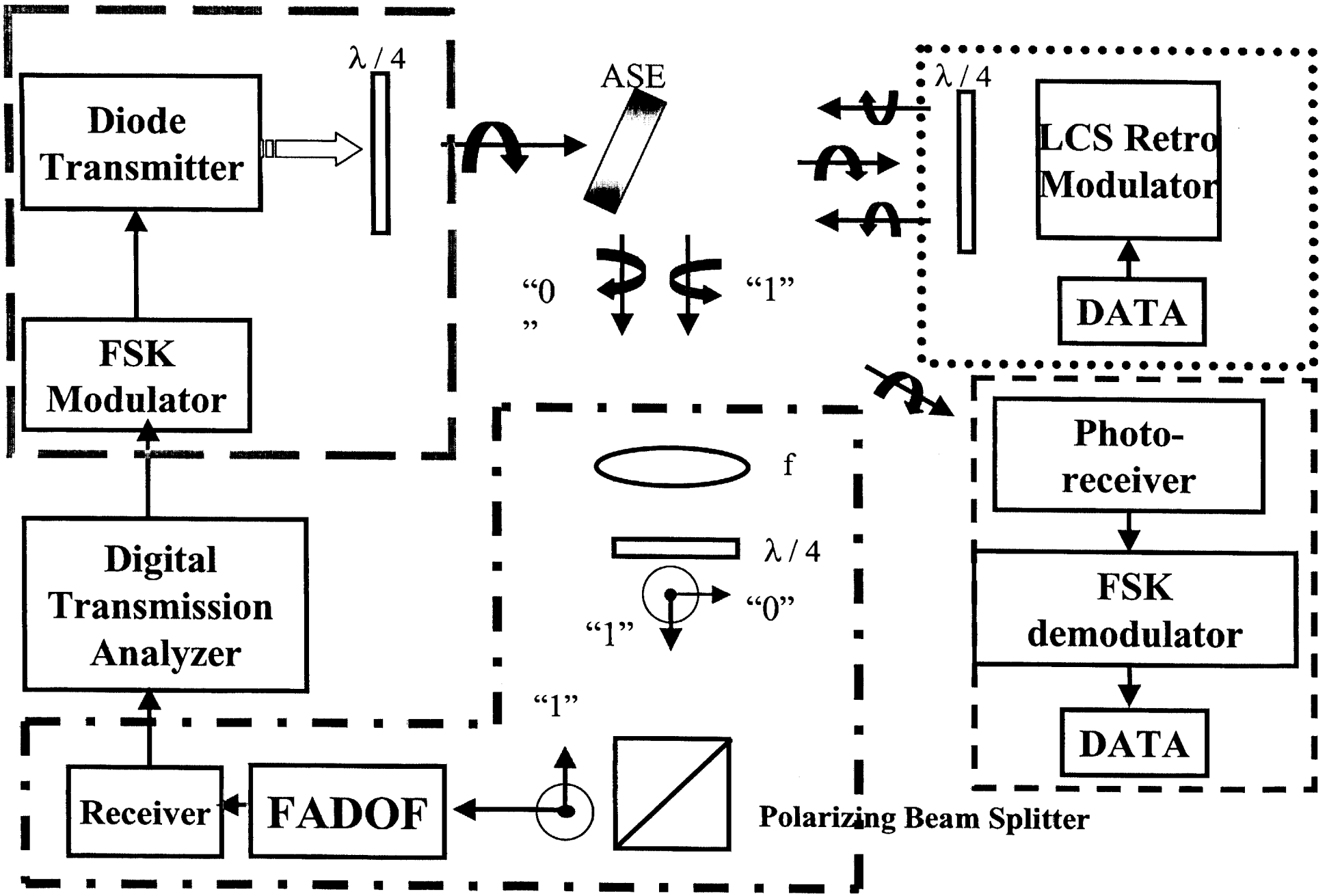


- 200 mW transmitter
- Full-Duplex by "Lightwire" *
- First Optical DD-CPK *

* Patent pending

LABORATORY EXPERIMENTS

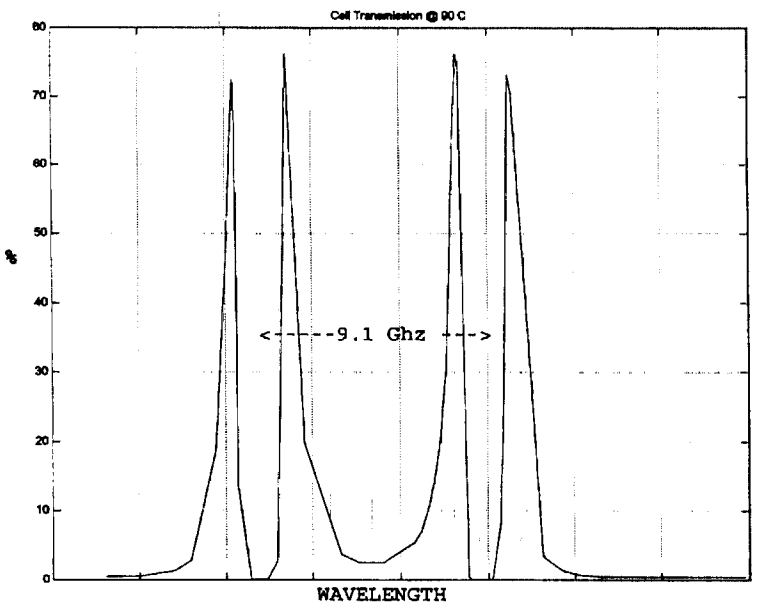
Lightwire: FSK and Circular Polarization Keying transparent link pair



Subsystem Tests

- **Liquid Crystal Shutter**
  - **Rise time 80 μs**
  - **Versus frequency**
    - **0.035 at 10 kbps**
  - **Power consumption**
    - **14 mW/cm^2**

- **FADOF**
  - **Throughput ~ 0.7**
  - **Transmission Spectrum**



Preliminary System Tests

- Downlink receiver
  - PMT
    - Quantum Efficiency = 1.1%
    - Gain = $5.2\ 10^5$
  - CPK link
    - SNR = 138
    - BER < $1.67\ 10^{-7}$ (no errors in 10 minutes at 10 kbps)
- Uplink Receiver
  - FSK demodulator
    - Easily operates at 20 kbps
  - FSK Link
    - SNR ~ 1000
    - BER < $1.67\ 10^{-7}$ (no errors in 10 minutes)

- **Lightwire Demonstration**
- **(Full Duplex on a single beam)**
  - BER < $1.67\ 10^{-7}$ (no errors in 10 minutes at 10 kbps)

SUMMARY OF MAJOR ACCOMPLISHMENTS IN FY 00-01

- First demonstration of DD-CPK optical communications
- First demonstration of Full Duplex on a single optical beam, "Lightwire"
- Demonstration of the Subcarrier FSK uplink receiver system
- All of the critical subsystems have been built and tested
- For the space experiment received signal levels no errors were detected over a 10 minutes period for any of the above link tests

GOALS FOR FY 01-02

- **Experimental Tasks**
  - **Perform short range field test**
  - **Design, build, and test DSP for uplink receiver**
  - **Add AGC's to uplink and downlink receivers**
  - **Design and implement data storage and data processing hardware for flight system**
  - **Finalize reflector design**
- **Design Tasks**
  - **Structural/thermal modeling and design for flight package**
  - **Safety review preparations**

Inter-Agency collaborations

- Army
  - Proving the WSMR APT ground station at no cost
  - Donating the use of the WSMR APT satellite tracking optical telescope
  - Donating the WSMR manpower required to operate the APT
- Air Force
  - Funding a second ground station at Maui
    - Funding 2.5 Gbps link at 1.5 microns
    - Funding a second NASA type link
- DOE (LANL)
  - Considering funding an additional experiment